Computational study of sloshing behavior in 3-D rectangular tank with and without baffle under Seismic Excitation

Thesis Submitted to

National Institute of Technology, Rourkela

In partial fulfillment of requirements

for the award of the degree

of

Master of Technology

In Mechanical Engineering with Specialization

"Thermal Engineering"

by

Puneet Kumar Nema (Roll No. 212ME3316)

Under the guidance of

Prof. A. K. Satapathy

DEPARTMENT OF MECHANICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

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ROURKELA

CERTIFICATE

This is to certify that the work in this thesis entitled "**Computational study of sloshing behavior in 3-D rectangular tank with and without baffle under Seismic Excitation**" by **Mr. Puneet Kumar Nema** (212ME3316) has been carried out under my supervision in partial fulfillment of the requirements for the degree of **Master of Technology** in Mechanical Engineering with **Thermal Engineering** specialization during session 2012 - 2014 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela.

To the best of my knowledge, this work has not been submitted to any other University/Institute for the award of any degree or diploma.

Date

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NOMENCLATURE

English Symbols

g	Gravitational acceleration
h	Fluid fill level
l	Length of tank
a,b	Phases
I	Unit tensor
VOF	Volume of fluid method
x, y, z	Co-ordinate axis
t	Time
Δt	Time step
Δx_{cell}	Cell size
c	Courant number
$\vec{F}$	Force vector(Momentum Source Term)
u, v, w	Velocity component
p	Pressure
A	Excitation amplitude

Greek Symbols

ν	Kinematic viscosity
ω	Angular frequency
α	Volume fraction
η	Slosh height
μ	Dynamic viscosity
ρ	Density
$\vec{\tau}$	Stress tensor
ε	Turbulence dissipation
μ_t	Turbulence viscosity

ABSTRACT

Sloshing in storage tanks for chemicals, water etc. is of great importance during earthquake seismic response considering safety factor. During earthquake, seismic excitations are generated, which can cause damage to the tank as well as loss of life and property. In chemical storage tanks, release of toxic chemicals or liquefied gases from the damaged tanks can lead to disastrous effects. Thus estimation of sloshing frequency of liquid in tank, hydrodynamic pressure on wall and proper analysis of fluid-tank interaction under seismic excitations is required for efficient design of storage tanks. In this present study, sloshing behaviour in a 3-D rectangular tank is investigated using ANSYS-FLUENT (Version 13.0) software, subjected to various seismic excitation frequencies, different fill levels in tanks, with and without baffles conditions for altered baffle heights. For simulation of two-phase flow in a 3-D tank equipped with baffles, partially filled with incompressible, viscous fluid, volume of fluid (VOF) method based on the finite volume method (FVM) has been used. External Seismic excitations to the tank are imposed by Momentum Source input in cell zone conditions using User defined Function (UDF). Simulation is being carried out for 20 sec by using variable time method. The purpose of the present work is to examine computationally the effect of earthquake frequency content on the seismic behaviour of rectangular water storage tank system and to check variation of baffle height relative to the initial liquid fill level, affects the sloshing phenomenon, when the tank with vertical baffle at the center of the bottom wall, seismically excited with frequency equal to natural frequency of the liquid in the tank. The analysis shows that if the tank is subjected to Seismic excitations at resonant excitation Frequencies, liquid sloshing will become extreme and wall forces will be intensified. Result shows that after a certain height (critical height) of baffle, the liquid does not reach at roof top and when baffle height is equal to liquid fill level, almost linear behavior of the free surface is observed in each section. . Time variation of pressure in relation to the baffle height is also investigated by monitoring at certain point in tank wall

Keywords: Liquid Sloshing, VOF method, baffle, seismic excitation, natural frequency, ANSYS-FLUENT.

Chapter 1

INTRODUCTION

1.1 General

Sloshing can be defined as any movement of the free liquid surface inside other object. This motion can be caused by disturbance to partially filled liquid containers. For sloshing, the liquid must have a free surface to constitute a slosh dynamic problem, where the dynamics of liquid can interact with container to alter the system dynamic significantly. Sloshing behavior of liquids within containers represents thus one of the most fundamental fluid-structure interactions. The movement of liquid having a free surface is important in varios engineering disciplines such as propellant slosh in spacecraft tanks and rockets, cargo slosh in ships and trucks transporting liquid (for example oil and gasoline), oil oscillation in large tanks, water oscillation in a reservoir due to earthquake, sloshing in pressure-suppression pools of boiling water reactors and several others.

The dynamic behavior of a free liquid surface depends on the excitation type and its frequency, container shape, liquid motion. The excitation to the tank can be periodic, impulsive, sinusoidal and random. It can create lateral, planar, non-planar, rotational, irregular beating, parametric, symmetric, asymmetric, pitching/yaw or combinational effects. In lateral harmonic excitation, the liquid surface display non-linearity of two types. First is large amplitude response and the second involves different forms of liquid behavior produced by coupling or instabilities of various sloshing modes.

Liquid sloshing and free surface motion is a common problem affecting not only the dynamics of flow inside the container, but also the container itself. The containers carrying the liquids, tanks used to store liquids have to withstand the complex dynamics of the transportation system, different ground motions which they are serving. This unavoidable motion of the container and the forces associated on the liquid inside it results in mostly violent and disordered movement of the liquid/gas (mostly air or vapor) interface or free surface.

Containers having liquid with a free surface should be moved with proper attention to avoid spilling and other damages. Whenever there is free surface of liquid, oscillations or liquid sloshing will be induced by acceleration of the container walls. Liquid sloshing problem involves the estimation of pressure distribution in the tank, moments and forces developed by fluid motion, and natural frequencies of the free surfaces of the liquid inside container. These above parameters can directly affect the dynamic stability and performance of moving containers. Generally, estimation of hydrodynamic pressure in moving rigid containers two distinct components. First one is caused by moving fluid with same tank velocity and is directly proportional to the acceleration of the tank. The second component represents free-surface-liquid motion and known as convective pressure.

Application of sloshing can be found in various industrial as well as real life circumstances. Some are:

- Sloshing in LNG carrier
- Sloshing in industrial packing machine
- Sloshing in storage tanks
- Sloshing in oil tanks
- Sloshing in railway compressors
- Sloshing in dams.
- Sloshing in automotive industry

1.2 Sloshing in Liquid Storage Tanks

Liquid storage tanks are vital components of lifeline and industrial facilities. Liquid Storage tanks are widely used in water supply facilities, oil and gas industries, nuclear plants for storage of a variety of liquid and wastes of different forms. The problem of liquid sloshing in moving or stationary containers is of great concern to Aerospace, nuclear and civil engineers, designers of road tankers, physicists, and ship tankers and mathematicians. Sloshing in oil tanks, large dams, elevated water towers is of great concern during earthquake induced ground motion for seismologists and engineers.

There are many types of storage tanks depending on the structure, construction material, content, volume, and storage condition. Liquid storage tanks can be built by steel or concrete. Due to extreme damages on steel tank, the concrete storage tanks are generally used nowadays. Reinforced Concrete (RC) has been used in environmental engineering structures such as water reservoirs and sewage treatment tanks. Water tanks are nowadays used enormously for varios applications, such as storage of drinking water, agricultural farming and livestock, fire suppression, and many other applications.

The liquid sloshing may cause huge loss of human life, economic and environmental resources due to unpredicted failure of the container. The spilling of toxic mixtures stored in tanks in industries can be the reason of soil contamination and can create adverse effect in environment. Thus, understanding the dynamic behavior of liquid free-surface is essential. Due to this many engineers and researchers are aiming to understand the complex behavior of sloshing and finding the ways to reduce its impact on structures and trying to develop structures to withstand its effect.

The fluid sloshing in storage tanks when excited by seismic excitation can cause a serious problem, Such as, tanks roof failure, fire of oil-storage tanks. Thus to avoid sloshing movement to impact tank roof, Maximum sloshing wave height (MSWH) is used to provide adequate freeboard for liquid surface. Large amplitude slosh waves are the main cause of nonlinear slosh effects. These waves appear when seismic wave frequency components coincide with the primary natural period (Resonance) frequency of earthquake excited motion for longer periods. When the wave amplitude is large enough to create dynamic effects on fluid container, change the free surface boundary condition, the hypothesis and assumption of linearized theory is not valid, thus non-linear effects of liquid should be taken into account and continuously update the moving boundary condition on free surfaces.

1.3 Background

Liquid sloshing in storage tanks due to earthquakes is of great concern and it can cause various engineering problems and failures of structural system. These damages include: Buckling of ground supported slender tank, rupture of steel tank shell at the location of joints with pipes, collapse of supporting tower of elevated tanks, cracks in the ground supported RC tanks, etc. During Alaska earthquake, many tanks suffered typical damage such as fire, buckling of floating roof caving of fixed roofs and failures on structural systems of tank. In Japan, many petroleum tanks were damaged by the sloshing during 1964 Niigata earthquake, 1983 Nikonkai-chubu earthquake and 2003 Tokachi-oki earthquake. Therefore, the stability of the liquid storage tanks under earthquake conditions must be studied carefully.

1.4 Linear Wave Theory

Linear wave theory is one of the first types of mathematical modeling used to analyse wave motion. It is the core theory of ocean surface waves used in ocean and coastal engineering and naval architecture and generally used to evaluate the seismic response of liquid storage tanks. It provides some insight into wave motion at a relatively simple level. Sloshing is often analyzed in a simpler form where no overturn takes place.

Mathematically it is based on the governing equation of continuity and potential flow assumptions. Assumptions like incompressibility, irrotational flow, inviscid (viscous/drag/friction terms are negligible), no ambient velocity (no current), and small amplitudes are also allowed for a simplified analysis via linear wave theory.

Linear wave theory for a 3-D liquid container yields following equation which represents the n^{th} mode oscillation frequency 'ω_n' in a container of length 'l' and fluid height 'h'.

$$\omega_n^{\,2} = \frac{n\pi g}{l}\tanh\left(\frac{n\pi h}{l}\right) \tag{1.1}$$

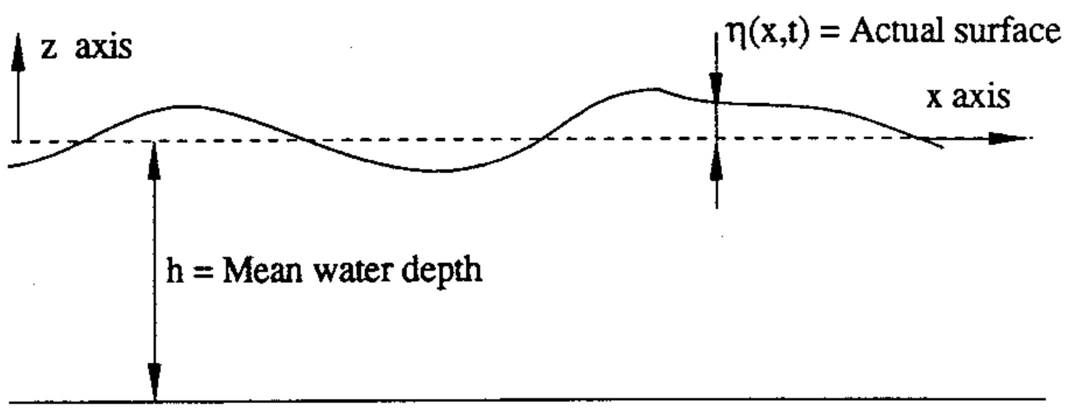


Fig 1.1: Linear Wave Motion

1.5 Fluid structure interaction (FSI)

Fluid-Structure Interaction refers to the coupling of unsteady fluid flow and structural deformation. It is a two-way coupling of pressure and deflection. Its application includes airbag modeling, fuel tank sloshing, heart valve modeling, helicopter crash landings, etc.
Purpose of studying FSI is that fluid mechanics may affect and be affected by the structural mechanics, and vice-versa. Hence in this case the coupling of the fluid's pressure and the motion of the structure is essential.

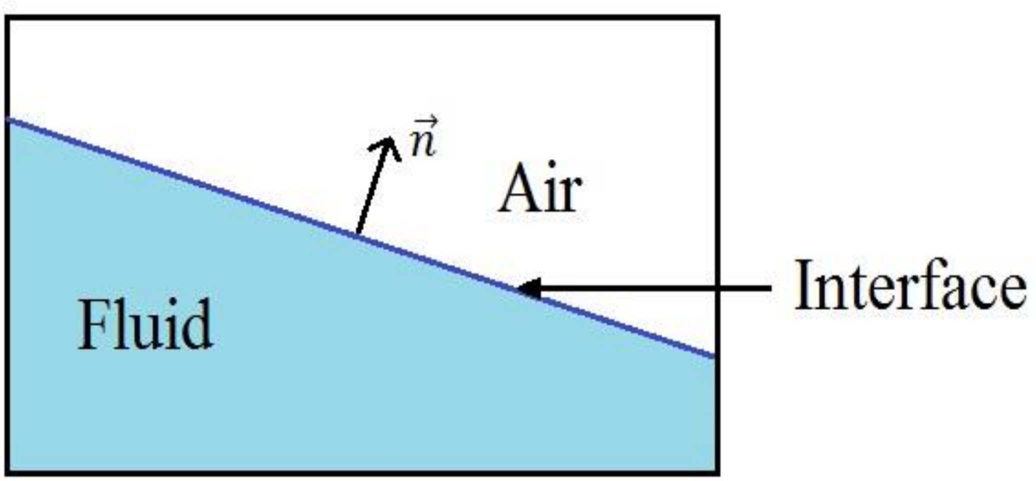


Fig 1.2: Fluid structure interaction

1.6 Free surface Representation

Several techniques exist for tracking immiscible interfaces, and these can be classified under three main categories according to physical and mathematical approach:

1. Moving Grid or Lagrangian approach (Capturing).
2. Fixed grid or Eulerian Approach (Tracking).
3. Combined method of Lagrangian and Eulerian.

Lagrangian approach includes moving-mesh, particle-particle scheme and boundary integral method. Eulerian approach can be divided into two main approaches: Surface tracking and Volume tracking. These include front-tracking, volume of method (VOF), Marker and Cell (MAC) method, smoothed particle hydrodynamics, level set methods, and phase field.

1.7 Computational Fluid Dynamics Packages

The first solution of sloshing problem was done in 1933 which determine pressure on rectangular, vertical dam when it is subjected to horizontal acceleration. After this tremendous amount of work has been done in the field of sloshing. Till 1990's these analysis were analytical and cumbersome process which requires calculation of Laplace's Equation so that boundary conditions will be satisfied. After the invention of computer and advent of modern computing capabilities, liquid sloshing phenomenon including its nonlinearity can studied and simulated computationally and numerically with higher amount of accuracy.

The availability of affordable high performance computing hardware and the introduction of user-friendly interfaces have led to the development of commercial CFD packages. Several general-purpose CFD packages have been developed in past decade. Prominent among them are: PHONICS, FLUENT, SRAT-CD,CFX, FLOW-3D and COMPACT. Most of them are based on the finite volume method.

1.8 Objective of present work

1. To study the concept of liquid sloshing.
2. To simulate liquid sloshing in a rectangular tank subjected to seismic excitation due to earthquake ground motion at different fill level by using ANSYS -FLUENT v13.0 software.
3. To study the effect of slosh forces and moment on stability and structural performance of liquid storage tank.
4. To study the effectiveness of vertical baffle for reducing slosh forces and moment.

1.9 Thesis Organization

This thesis has been prepared in seven chapters.

Chapter 1 presents a general introduction of sloshing and its effect. Basic theory which is used in present study and computational background is also discussed.

Chapter 2 presents available work which has been done in the field of sloshing and is used in present work.

Chapter 3 presents the problem formulation and physical model of present study.

Chapter 4 discussed mathematical formulation and governing equations which are solved to obtain the solution.

Chapter 5 describes the computational work and setup of ANSYS-FLUENT with procedure followed.

Chapter 6 presents the final result we obtained in our present simulation.

Chapter 7 presents the conclusion of present study and some scope of future work which can be done in field of sloshing.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This section of the thesis provides an overview of some of the major fields of interest either utilized or examined in this work. This survey of literature is expected to provide the background information and thus to select the objectives of the present investigation on sloshing in rectangular storage tanks. Some Computational as well as Numerical work has been investigated throughout this work and utilized here.

2.2 Importance of sloshing

Study of sloshing was first initiated by Graham in the year 1951 when he developed an equivalent pendulum to represent the free surface oscillations of a liquid in stationary tank. Graham and Rodriguez (1952) introduced another model consisting of sloshing point mass attached with springs to the tank wall at a specified depth and a fixed rigid mass.

Initially aeronautics was the major field of interest, where the motion of fuel is studied in tanks that would adversely affect the dynamics and stability of a plane. Fuel tanks in rockets were also a major topic for study of sloshing initially. More recently, the motion of liquids, including fuels, in several naval applications and its structural & enormous effects attracted much attention.

Further fields of attention include the aerodynamic and seismic equilibrium of tall structures and its acoustical effects of fuel sloshing in vehicle fuel tanks and storage tanks.

The problem of sloshing in closed vessels has been subjected of several studies over the past few decades. The phenomenon of sloshing involves free surface movement of the fluid in the container due to sudden loads. Free surface liquid motion is very important factor in liquid storage tanks, airplanes fuel containers, space vehicles, missiles and satellites. Forces on liquid container’s wall and moments will be severe when they are excited by frequencies near to resonant. Thus to avoid failures, estimation of dynamic loads is necessary.

2.3 Computational Studies

Ling Hou et al. [1] studied sloshing performance in a 2-D rectangular tank. In this study, transient analysis is performed under single and multiple-coupled external excitations for two different frequencies using ANSYS-FLUENT software. Volume of fluid (VOF) method was used to track the free surface of liquid and dynamic mesh technique to impose external excitation. The result shows that at coupled excitations and near resonant excitation frequencies, sloshing behavior will become violent and sloshing loads, including impact on the top wall, will be intensified.

J.H. Jung et al. [2] investigated the effect of the vertical baffle heights on the liquid sloshing in a three-dimensional (3D) rectangular tank with 70% water fill level. He selected various ratios of baffle height (h_B) to initial liquid height(h).For simulation of 3D incompressible, viscous, two-phase flow in a tank partially filled with liquid and equipped with baffles, the volume of fluid (VOF) method based on the finite volume method has been used. Result shows that after a certain height (critical height) of baffle, the liquid does not reach at roof top and when baffle height is greater than liquid fill level, free liquid surface exhibit linear behavior in each section.

Vaibhav singal et al. [3] studied sloshing phenomenon in a partially filled kerosene tank using volume of fluid (VOF) multiphase model with and without the use of baffles. Computational study was done using Finite volume method in ANSYS-FLUENT software. Result shows that sloshing in the fuel tank was effectively reduced with the use of baffles in the tank.

Krit Threepopnartkul et al .[4] studied the effect of baffles on reducing severe sloshing inside moving rectangular tank. He used Finite volume method for analyzing fluid sloshing in tank. Computational models were used to investigate effects of baffles. This study has been done using C++ codes implemented in the Open Source software i.e. OpenFOAM. The whole simulation was done experimentally as well as computationally and both the results were digitized using the image processing techniques having the average error less than 3.73%.

S. Rakheja et al. [5] studied effectiveness of different design of baffle, including lateral, oblique, conventional and partial under longitudinal and lateral acceleration for different fill levels in a 3-D truck tank. This analysis was done using ANSYS-FLUENT software with volume of fluid (VOF) model for tracing of interface between two fluids. The result shows that the conventional lateral baffles are more effective to fluid slosh under longitudinal acceleration only while the oblique baffle helps to reduce both longitudinal as well as lateral slosh forces.

Kingsley et al. [6] studied about design and optimization of 3-D rectangular container for sloshing and impact using VOF technique. They performed the investigation using numerical simulation as well as experimental validation. For numerical simulation k-Ɛ turbulence model for viscous effects and an acceleration user defined function (UDF) input was imposed for motion of tank.

Bernhard Godderidge et al. [7] used experimental and commercial CFD code to study sway-induced sloshing flow in a rectangular tank. During investigation they compared homogeneous and inhomogeneous multiphase approach for fluid density and viscosity. The comparison between the computational and experimental results shows that the homogeneous model gives less accurate results for peak pressures up to 50% as compared to inhomogeneous multiphase model.

A.Vakilaad Sarabi et al. [8] studied the effect of ground motion on sloshing inside a rectangular tank. For this purpose they used computational fluid dynamics (CFD) simulation tool OpenFOAM (Open Field Operation and Manipulation).A VOF technique is used to assure an accurate description of water displacement. Results shows that the intensity of sloshing and pressure loads depend on the tank geometry, fill level, amplitude, frequency of excitation.

A. Di Nardo et al. [9] evaluated the behavior of liquid fuel storage tanks of cylindrical shape (diameter = 10 m, height = 11m) when subjected to an earthquake. The analysis was done with the help of a CFD software. The simulations were made for different filling levels, subjecting to 7 different acceleration inputs. Results are presented and show that sloshing of fluid depends on excitation frequency and filling levels.

M. Eswaran et al. [10] studied the sloshing waves in baffled and without baffled cubic tank using VOF technique with Arbitrary-Lagrangian–Eulerian (ALE) formulation. ADINA software was used for simulation of coupled system which is based on Finite Element method. The results show sloshing effects in fluid model can effectively reduced by the application of baffle.

Mahmood Hosseini et al. [11] studied dynamic analysis of sloshing in rectangular tanks with multiple vertical baffles. ANSYS-CFX software was used to study this dynamic analysis subjected to random excitations including earthquake induced motions. Results show the relationships between the frequency, base excitation amplitude and the maximum level of liquid in the tank during the sloshing.

2.4 Numerical and Experimental studies

Lyes Khezzar et al. [12] done experimental study on a test rig (560 x 160 x 185 mm rectangular container) to study water sloshing phenomenon subjected to sudden (impulsive) impact. Motion of fluid was recorded using a video camera. Two water fill levels of 50 and 75% with two driving weights of 2.5 and 4.5 kg were used. Finally, flow fields, obtained using the numerical code were compared with experimental results.

Dongming Liu et al. [13] developed a numerical model for liquid sloshing in a 3-D tank with baffles. The spatially averaged Navier–Stokes equations were solved numerically. The large-eddy-simulation (LES) approach is used to model turbulence by using the Smagorinsky sub- grid scale (SGS) closure model. The baffles are modeled by virtual boundary force (VBF) method. The numerical model is validated against the analytical solution and experimental data for 2-D as well as 3-D liquid sloshing in a tank with and without baffles.

Mi-An Xue et al. [14] numerically solved Navier-Stokes equations for investigation of liquid sloshing phenomenon in a cubic tank with various configurations of horizontal baffle, perforated vertical baffle, and their combined configurations under the harmonic motion excitation. Experimental testing of liquid sloshing in cubic tank with perforated vertical baffle was simulated to validate numerical results.

Y.G. Chen et al. [15] simulated sloshing in a partially filled tank excited by dynamic load to calculate the impact pressure. For free surface representation, Reynolds-averaged Navier–Stokes (RANS) is used which a two-fluid approach based on a level set method. For numerically investigation purpose, rectangular tank was excited by horizontal harmonic motion and harmonic rolling motion. Simulation is done for different filling levels and excitation frequencies. The computed results were compared with experimental data and show that simulation of dynamic pressure loads exerted on the tank walls and ceiling can be done very effectively with numerical methods.

M. A. Goudarzi et al. [16] analytically estimated hydrodynamic damping ratio for liquid sloshing phenomenon in a partially filled rectangular tank for baffles. They used the velocity potential formulation and linear wave theory for analytic calculations. For validation of analytically obtained results, they experimentally excited the rectangular tank with harmonic oscillation frequencies and results were compared. Different baffle configuration (both vertical and horizontal) at different locations and dimensions are studied to analyse their damping efficiencies.

P.K. Panigrahy et al. [17] experimentally estimated pressure generated on the tank walls and the water surface displacement from the mean static level in liquid sloshing phenomenon in a square tank. The tank is tested for both with and without baffle configuration, where DC motor power is used to oscillate it. Displacement and Pressure are calculated by changing excitation frequency and fill level in the tank.

Hakan Akyildiz et al. [18] experimentally calculated non-linear behavior, damping characteristics, pressure variations and liquid sloshing loads for both baffled and without baffled configuration of a 3-D rectangular storage tank.

S. Hashemi et al. [19**]** analytically determine the dynamic effect of 3-D rectangular fluid container (for both rigid and flexible wall) excited by earthquake ground motion. Rayleigh–Ritz method is used to consider the effects on the dynamic responses of fluid containers. Using this model the maximum seismic loading of the tank base can be predicted. To evaluate pressure distribution on the tank wall, a 2-D model is also developed. The results show the variation in hydrodynamic pressure distributions for both walls in magnitude and shape. The variation is in vertical as well as in horizontal direction over the tank wall.

K. C. Biswal et al. [20] studied the effect of nonlinearity on the dynamic behavior of liquid filled rectangular tanks. For this simulation they developed a velocity potential based 2D Galerkin FEM. Mixed Eulerian-Lagrangian-material –node time-marching scheme is used for numerical solution at every time step. To track the free surface Fourth-order Runge-Kutta scheme was used. Result shoes that nonlinear movement of liquid does not have significant effect in the pressure distribution on the tank wall but has effect on base shear, base moment and sloshing amplitude.

2.5 Closure:

In this chapter various research work is presented about sloshing. Many papers have been published; some investigated computationally, some experimentally and numerically predicted sloshing behavior. Sloshing because of its non-linear behavior is a real challenge for engineers. Techniques which are used nowadays are new and require validations. Numerical solutions are done using solving governing equations by different techniques, but it also require validation with commercially available codes.

Chapter 3

PHYSICAL MODEL

Project model and problem specification of present work is explained in detail.

3.1 Physical Model

The physical model used for present study is shown in figure. Present model consists of a 3-dimensional liquid storage rectangular tank which is partially filled with water (ρ=999.98 kg/m^3, μ=0.00103 kg/m-s). The tank dimensions are 1.2*0.6*1.2 m^3. Water fill level in tank is 60% and 80% of total height of tank and the rest part is occupied with air. During the seismic excitation mode, tank is supposed to go under sloshing effect which creates pressure and forces on tank wall. During computation, pressure is monitored at a certain point on the right wall in order to record the sloshing loads.

To reduce the effect of sloshing on tank wall, tank is equipped with vertical baffle of thickness 2mm and of different height which depends on fill level of water inside tank. The details of various dimensions of physical model are presented in figure.

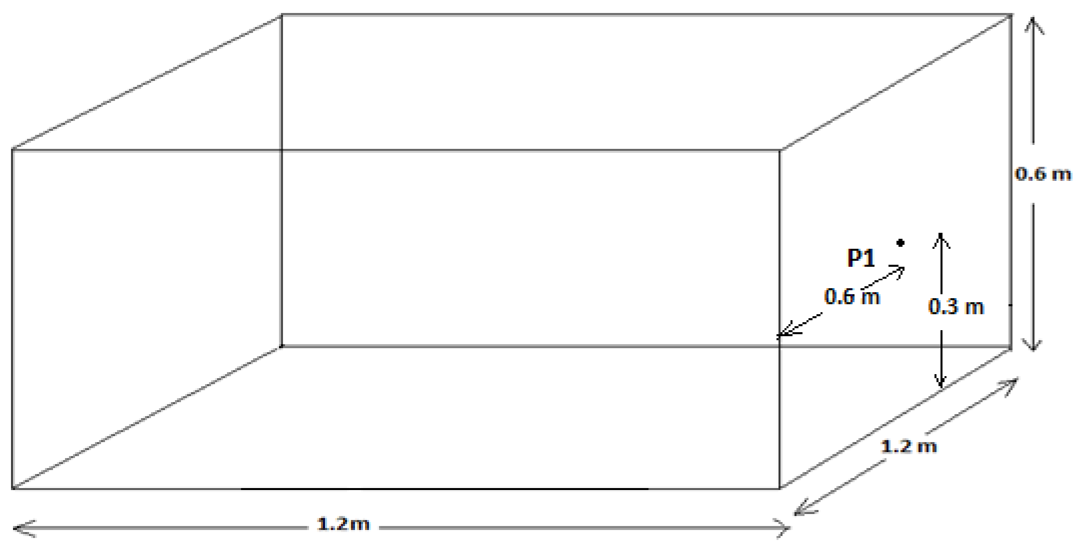


Fig 3.1: Water Storage Tank

3.2 Motion of the tank

The study has been done for two different cases of seismic excitation frequency and magnitude of 0.015 m/s^2.

i. When the storage tank is subjected to seismic excitation of natural frequency i.e. ω_n for 60% fill and 80% fill water level, with and without baffle and magnitude of amplification is taken as 0.015 m/s^2.

ii. When the storage tank is subjected to seismic excitation of frequency less than natural frequency i.e.0.93ω_n for 60% fill and 80% fill water level, with and without baffle and magnitude of amplification is taken as 0.015 m/s^2.

3.2.1 Sinusoidal motion of tank

The motion of the rectangular tank is purely based on sinusoidal base excitation. The tank is excited with an amplitude of 0.015 m/s^2. Motion of the tank can be represented by:

$$\left.\begin{aligned} x &= A\sin(\omega t) \\ \dot{x} &= A\omega\cos(\omega t) \\ \ddot{x} &= -A\omega^2\sin(\omega t) \end{aligned}\right\} \tag{3.1}$$

Where x is displacement, $\dot{x}$ is horizontal translational velocity, $\ddot{x}$ is horizontal acceleration, A is the horizontal displacement amplitude, ω is the angular frequency and t is time period of oscillation.

3.3 Tank with baffle

Sloshing occurs due to motion of fluid inside partially filled tank. So to reduce the severe effect of sloshing baffles are introduced in tank at appropriate locations. In the present study, simulation is done with and without baffle and studied the effectiveness of different height of baffle on sloshing forces and pressures exerted on tank wall. The baffle of thickness 2mm is included at the center of the tank vertically parallel to YZ plane.

The geometry for the present study is shown below:

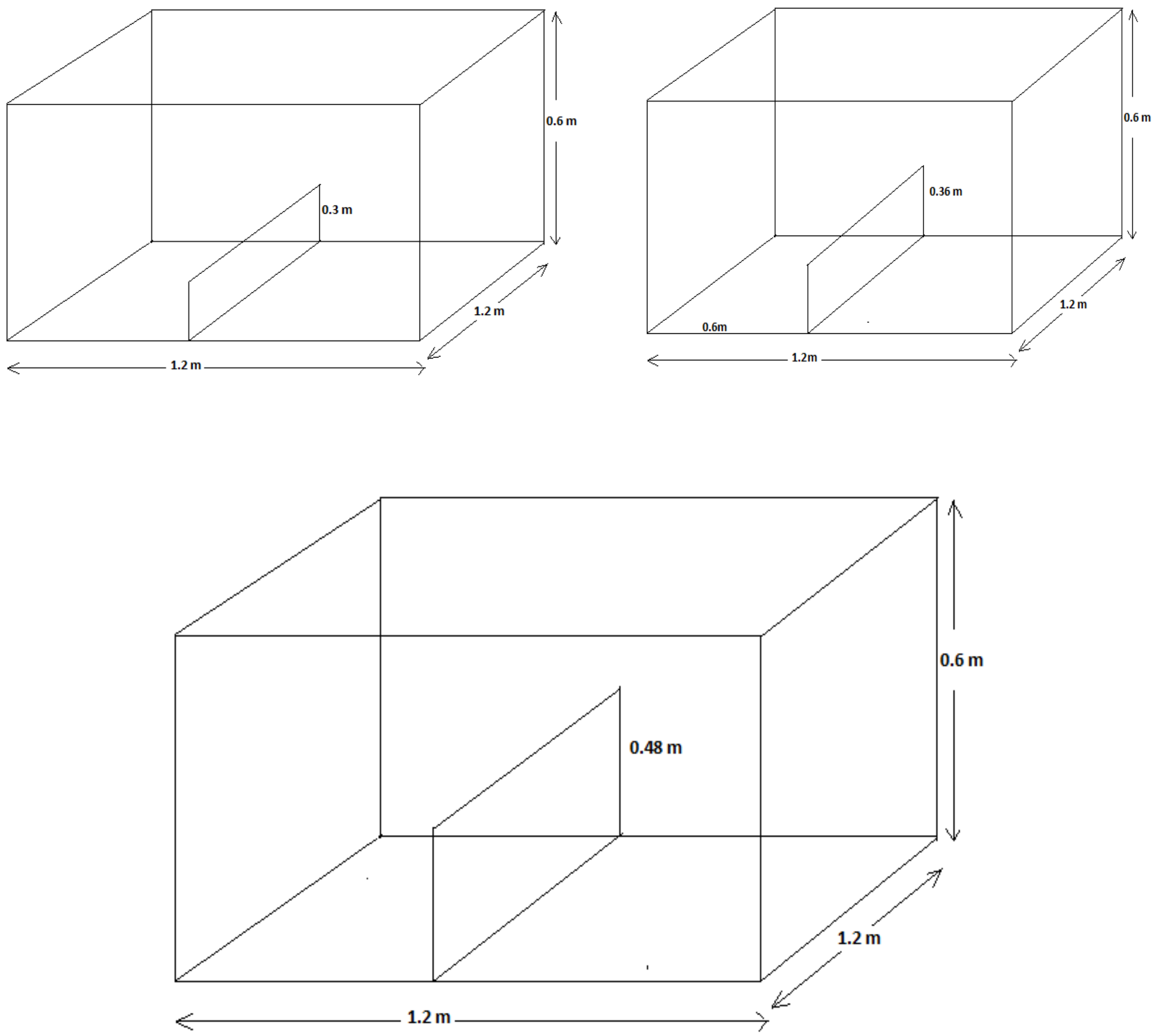


Fig 3.2: Tank with Baffle

3.4 Closure:

In this section, physical model, sinusoidal motion of tank, and baffle configuration in tank is explained.

Chapter 4

MATHEMATICAL FORMULATION

This chapter includes the details of mathematical modeling and solution methods used for study of sloshing. The mathematical equations describe the flow of liquid in case of sloshing including the motion of the free surface. It is the representation of physical event through mathematical equations. Since the physical events are difficult to model exactly, these equations provide an exact representation of reality. Computational Fluid Dynamics (CFD) techniques are used to solve the governing equation of sloshing numerically. The equations which are used to study sloshing here are: Continuity equation, Navier-stokes equation, and VOF.

4.1 Continuity Equation

Continuity equation used to describe the transport of conserved quantity. It also defines the conservation of mass.

For 3-dimensional continuity equation for unsteady flow is as follow:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{4.1}$$

where ‘ρ’ is the density, ‘t’ is time, and u, v, w are velocity components in x, y, z direction.

For incompressible and steady flow, continuity equation can be written as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{4.2}$$

4.2 Navier-Stokes Equation

Navier-Stokes equations describe the relation between velocity, pressure, temperature, viscosity and density of a moving fluid. This equation is valid for turbulent as well as laminar flow.

$$\frac{\partial(\rho u)}{\partial t}+\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=\rho x-\frac{\partial p}{\partial x}+\frac{1}{3}\mu\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)+\mu\nabla^2 u \tag{4.3}$$

where 'ρ' is the density, 't' is time, 'p' is pressure, μ is dynamic viscosity, and u,v,w are velocity components in x,y,z direction.

4.3 Multiphase governing equations

4.3.1 Conservation of momentum

The momentum equation is dependent on the volume fractions of all phases through the properties ρ and μ.

$$\frac{\partial}{\partial t}\left(\rho\vec{V}\right)+\nabla.\left(\rho\vec{V}\vec{V}\right)=-\nabla p+\nabla.\left(\vec{\tau}\right)+\rho\vec{g}+\vec{F} \tag{4.4}$$

where 'ρ' is the density, 't' is time, 'p' is the static pressure, μ is dynamic viscosity, $\vec{\tau}$ is the stress tensor, $\rho\vec{g}$ and are the gravitational body force and external body force respectively. $\vec{F}$ is used here for user-defined source terms, e.g. momentum source which is product of the density of a specific mesh cell and the instantaneous acceleration having units of kg/m^{2}s^2.

Momentum source terms is as follows,

$$\left.\begin{aligned}\vec{F}&=\rho * Acceleration\\ \vec{F}&=\rho * A\omega^2\sin(\omega t)\end{aligned}\right\} \tag{4.5}$$

The stress tensor is as follows:

$$\vec{\tau}=\mu\left[\left(\nabla\vec{V}+\nabla\vec{V}\right)-\frac{2}{3}\nabla.\vec{V}I\right] \tag{4.6}$$

Where is dynamic viscosity, $\vec{\tau}$ is the stress tensor, I is the unit tensor, and term after negative sign is an effect due to volume dilation (size change).

4.3.2 Turbulence modeling

To consider the effect of turbulence fluctuations time-average of Navier-stokes equation should be taken, which is known as Reynolds-Averaged Navier-Stokes equation. In present study we consider k -ε turbulence model which assumes the relation between Reynolds stresses in the fluid and mean velocity gradients.

The turbulence viscosity can be determined by following equation:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{4.7}$$

where k is turbulent kinetic energy, μ_t is turbulence viscosity, C_μ is constant of proportionality whose default value is 0.09 in fluent, ε is the turbulence dissipation rate.

4.3.3 Volume of fluid model

Volume of fluid (VOF) technique is used for tracking the free surface (or fluid-fluid interface) between the phases. This model was developed by Hirt, et al. This is developed to estimate the interface for two or more immiscible fluid. This model solves total continuity equation and the result is pressure and volume fraction which shows where the interface is. VOF model can find applications in stratified flows, sloshing, free-surface flows, the motion of liquid after a dam break, the motion of large bubbles in a liquid and tracking of any liquid-gas interface.

4.3.4 Volume Fraction

The principle of VOF model formulation based on the fact that there is no interaction between all the fluid phases. To define a new fluid or phase, the volume fraction of the phase in the computational cell will be introduced. For each control volume, the volume fraction of all the phases sums to unity. Each and every phase is represented by volume averaged value, depends on the volume fraction of the phases at different locations. Thus the variable and properties in any given cell either comprises of one phase, or a combination of the phases which depends on the volume fraction value. If α_b represent the b^{th} fluid's volume fraction in the cell then the following three conditions are possible:

i. $\alpha_b = 0$, shows the cell is empty (no fluid of b type is present).

ii. α_b = 1, shows the cell is full (only b type fluid is present).

iii. 0 < α_b < 1, shows the cell contain the interface between the b^{th} fluid and one or more other type of fluid.

4.3.5 Equation of Volume Fraction

The following equation is used to track the free surface and interface between the phases. For b^{th} phase, the equation will be:

$$\frac{1}{\rho_b}\left[\frac{\partial}{\partial t}(\alpha_b\rho_b)+\nabla.\left(\alpha_b\rho_b\vec{V_b}\right)=s_{\alpha_b}+\sum(\dot{m}_{ab}-\dot{m}_{ba})\right] \tag{4.8}$$

where $\dot{m}_{ab}$ is mass transfer from a to b phase and $\dot{m}_{ba}$ is mass transfer from b to a phase. s_{α_b} shows the source term which permits the use of cavitation model.

For n phases,

$$\sum_{b=1}^{n} \alpha_b = 1 \tag{4.9}$$

Following equation is used to calculate physical parameters in the two-phase flow for a & b:

$$\left.\begin{aligned}\rho &= \alpha\rho_b+(1-\alpha)\rho_a\\ \mu &= \alpha\mu_b+(1-\alpha)\mu_a\end{aligned}\right\} \tag{4.10}$$

where α is defined as,

α =1, water

α = 0 , air

4.3.6 Representation of VOF method

VOF model can be represented using the following figure, where the dark zone represents water and the remaining part represents air.

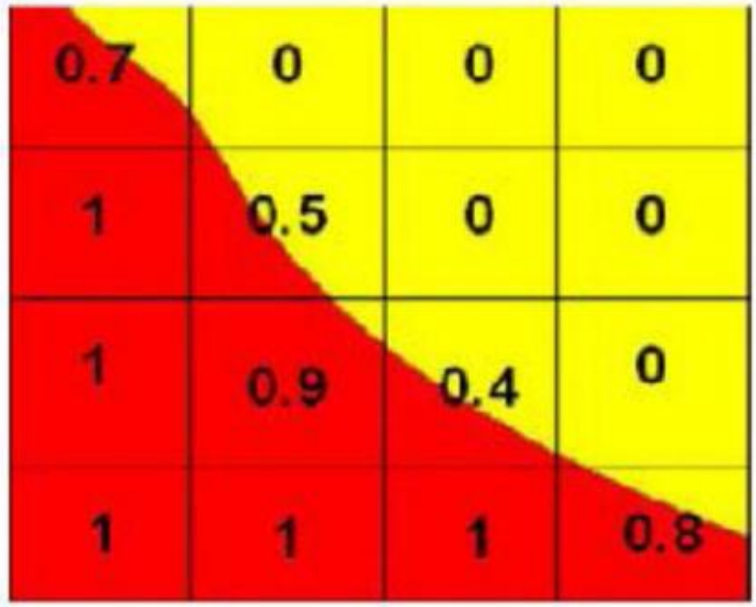


Fig 4.1: VOF model representation

The marked values in the cell represent the volume fraction of water. Zero cell value ($\alpha_{water} = 0$) shows the absence of water and where the cell value is unity ($\alpha_{water} = 1$), it shows the absence of air. In-between values signify the interface between the two fluids.

4.4 Closure

Present chapter gives the brief explanation of all the equations which are solved to simulate liquid sloshing problem. Continuity, Navier-stokes equation and equations required to understand the free liquid surface with VOF technique are discussed mathematically

Chapter 5

COMPUTATIONAL STUDY

This chapter presents introduction to computational fluid dynamics (CFD) and its various field of application in industry. In this chapter discretization methods, CFD simulation flows process. ANSYS Workbench and FLUENT setup is presented.

5.1 Computational Fluid Dynamics (CFD)

CFD is the science of envisaging fluid flow, heat transfer, chemical reactions, and associated phenomena by solving numerically the governing mathematical equations.

For simulation of any problem, computers are used to accomplish calculations. This technique is powerful tool and used widely in industrial and non-industrial applications.

5.2 CFD or Numerical Approach

In CFD, non-linear partial differential equations are solved by numerical techniques. In this methodology equations are discretized in linear algebraic form using Finite Difference, Finite Element, and Finite Volume methods and then solved by TDMA or Gauss-Siedel method.

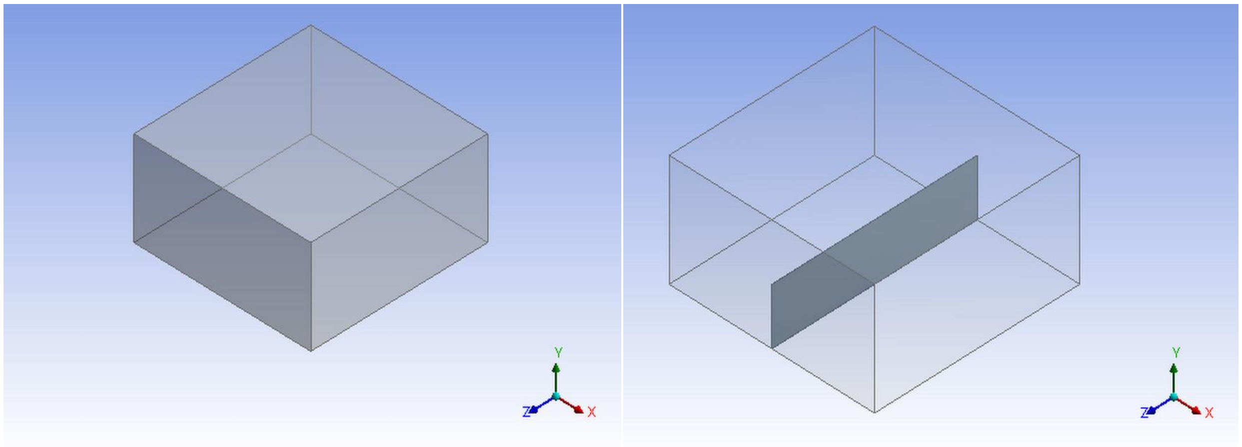
5.3 Ansys-Fluent CFD Platform

ANSYS Fluent is a influential general-purpose CFD software platform used to model flow, heat transfer, turbulence, and reactions for engineering applications. The physical prototypes allow precise CFD analysis for an extensive range of fluids complications.

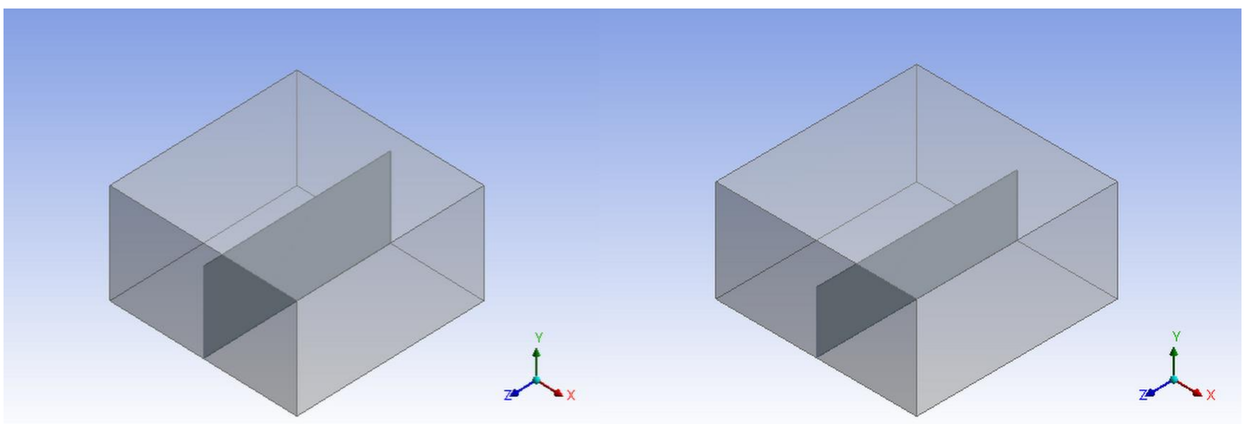
5.4 Ansys-Fluent Setup

In present study, simulation of water sloshing in a 3-dimensional rectangular storage tank is done by using ANSYS FLUENT v.13.0. In ANSYS, workbench platform is used for modeling geometry and generation of mesh. After meshing, mesh file is exported to FLUENT solver and Post-processing is done.

Geometry Modeling: A 3-Dimensional rectangular tank of dimension 1.2m length, 1,2m width and 0.6m height, without baffle and with vertical baffle of height 0.3m, 0.36m.0.48m is drawn in ANSYS DESIGN MODULUR (DM). Thickness of baffle is taken as 2mm.



(a) Tank without baffle **(b) Tank with 0.3m baffle**



(c) Tank with 0.48m baffle **(d) Tank with 0.36m baffle**

Fig 5.1: Tank Modeling in Ansys

Mesh Generation: After creation of geometry, meshing is done in meshing tool. In present case uniform quadrilateral mesh is generated for all cases.

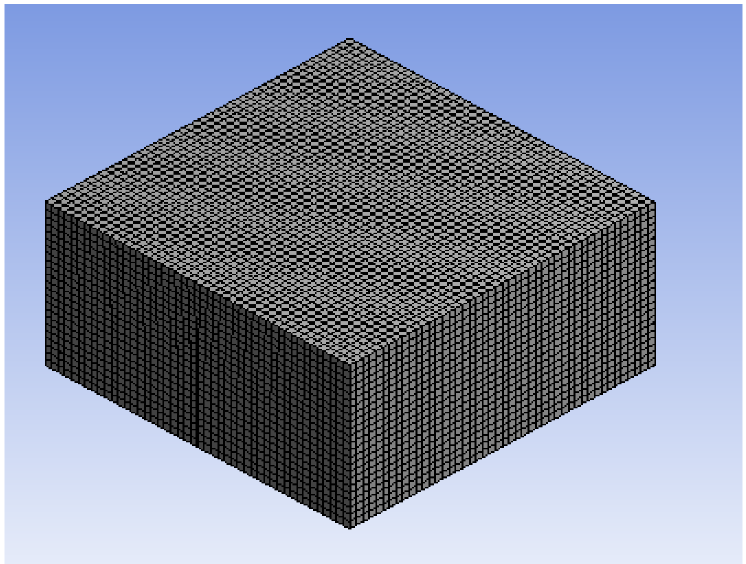


Fig 5.2: Meshing of tank

Fluent Setup: Once meshing is being done, mesh file is exported to CFD code FLUENT. In the present study 3-D, double precision fluent solvers with serial processing is used.

Following procedure is followed in Fluent:

1. In setup, it is scaled to proper units if required and mesh quality is checked.
2. Pressure based transient solver is used with explicit formulation and gravitational field is enabled.
3. Multiphase model with volume of fluid (VOF) method is used, and turbulent model is considered.
4. Air and water are used as two different immiscible fluids and aluminum is used as solid material.
5. Air is considered as primary phase and water as secondary.
6. For sinusoidal motion of tank acceleration imposed in the form of momentum source input.
7. For simulation following operating conditions are chosen:
    - Operating pressure:-101325 Pa
    - Gravitational acceleration:

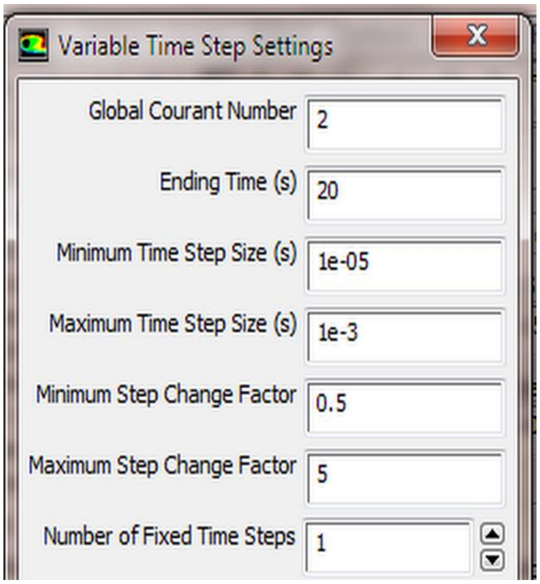
      X= 0 m/s^2

      Y= -9.81 m/s^2

$Z = 0\ m/s^2$

- Operating density:-1.225 kg/m^3

8. Baffle, baffle shadow and rectangular tank are considered as wall.
9. Following solution method is adapted:-
   - Pressure-velocity coupling : Fractional step
   - Gradient : least square cell based
   - Pressure : Body force weighted
   - Momentum : Power law
   - Volume fraction : Geo-Reconstruct
   - Transient formulation :Non-iterative time advancement
10. Non-iterative relaxation factor:-
    - Pressure : 0.8
    - Momentum : 0.6
11. For filling of water in tank, region of cell is adapted and then adapted cell is patched by water.
12. To display results in 3-d model iso-surface option has been selected. It is used to track points on free surface of water.
13. Time Stepping Method: Explicit formulation is used for simulation of sloshing. Hence for stability condition and avoid divergence, value of global Courant Number should not exceed 250. In variable time method:



5.5 Closure:

The presented chapter discussed about CFD and its various applications. Comparison between different problem solving techniques (experimental, analytical and CFD) is discussed.

ANSYS-FLUENT solver theory and steps included are also described.

Chapter 6

RESULT AND DISCUSSION

This chapter presents a detailed discussion about the result of the present study. For present sloshing problem, computational simulation is carried out for a 3-D liquid storage tank when it is subjected to earthquake ground motion and excited by seismic frequencies. Because of this sinusoidal motion of tank, forces and pressures developed in tank wall due to water impact. Simulation is carried out with and without baffle.

6.1 Case 1: When storage tank is subjected to Seismic Excitation of Natural frequency (ω_n) without baffle.

6.1.1. Below fig 6.1 and fig 6.2 shows the graph for longitudinal forces variation vs. time at different fill level 60% and 80%, when the tank is excited by natural frequency with excitation amplitude of 0.015 m/s^2.

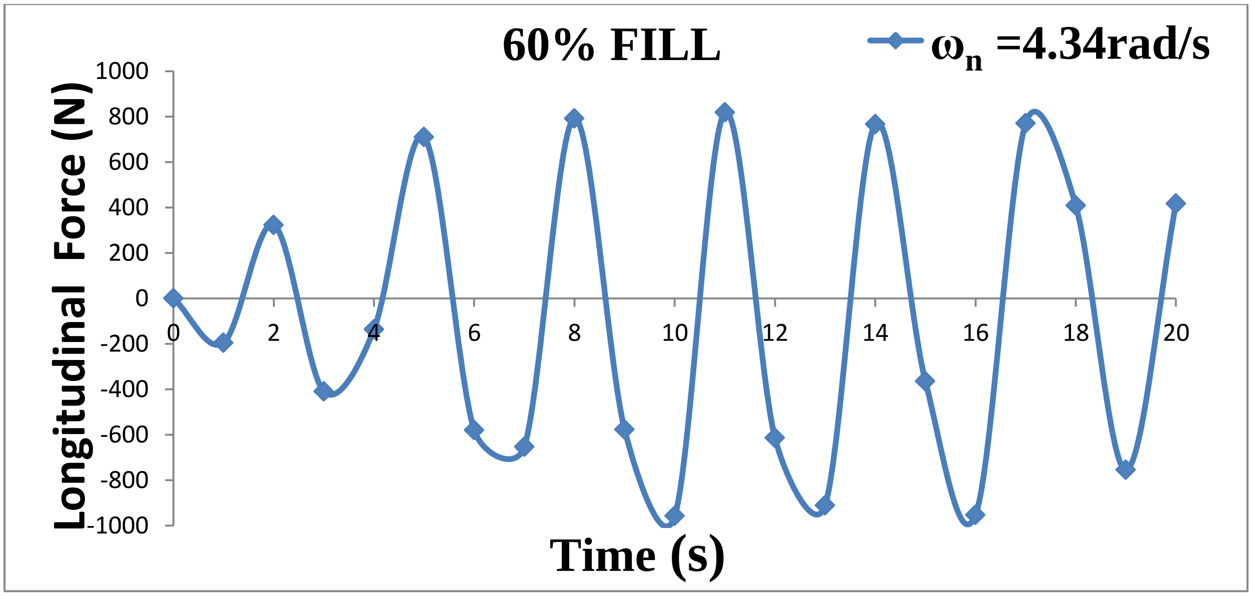


Fig 6.1: Longitudinal forces at 60% fill at Natural frequency (ω_n)

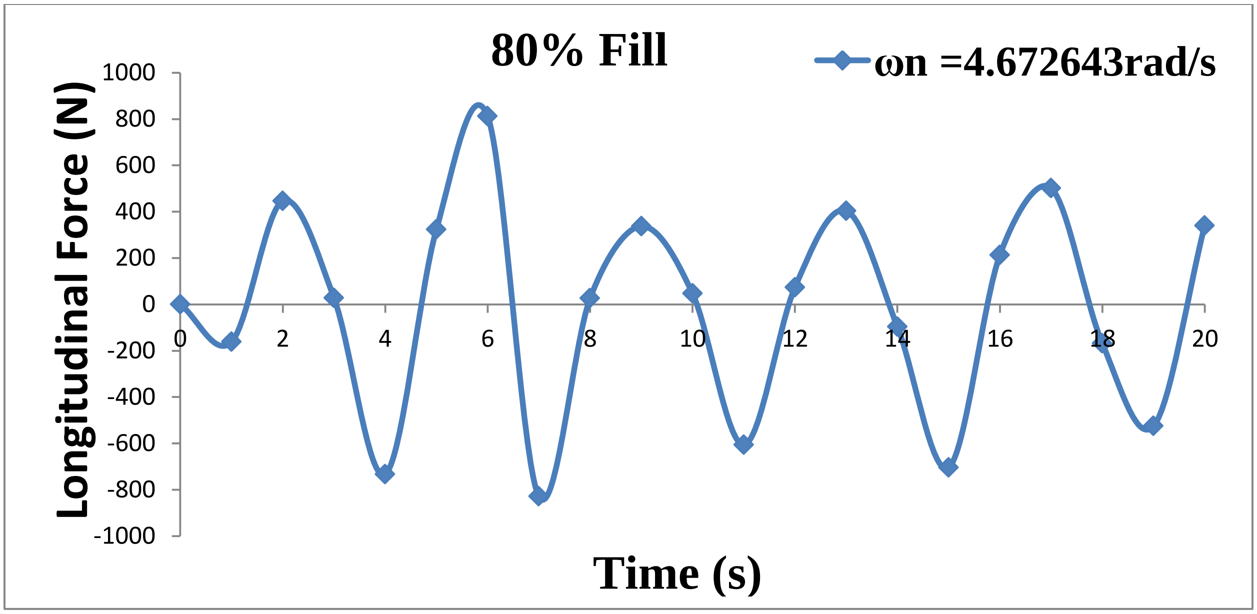


Fig 6.2: Longitudinal forces at 80% fill at Natural frequency (ω_n)

From above graphs fig. 6.1 & fig 6.2 it is clear that maximum amplitude of longitudinal forces is higher at low fill level, because at higher fill level of fluid, slosh does not occur heavily.

6.1.2. Below fig 6.3 & fig 6.4 shows the graph for lateral forces variation vs. time at different fill level 60% and 80%, when the tank is excited by natural frequency with excitation amplitude of 0.015 m/s^2

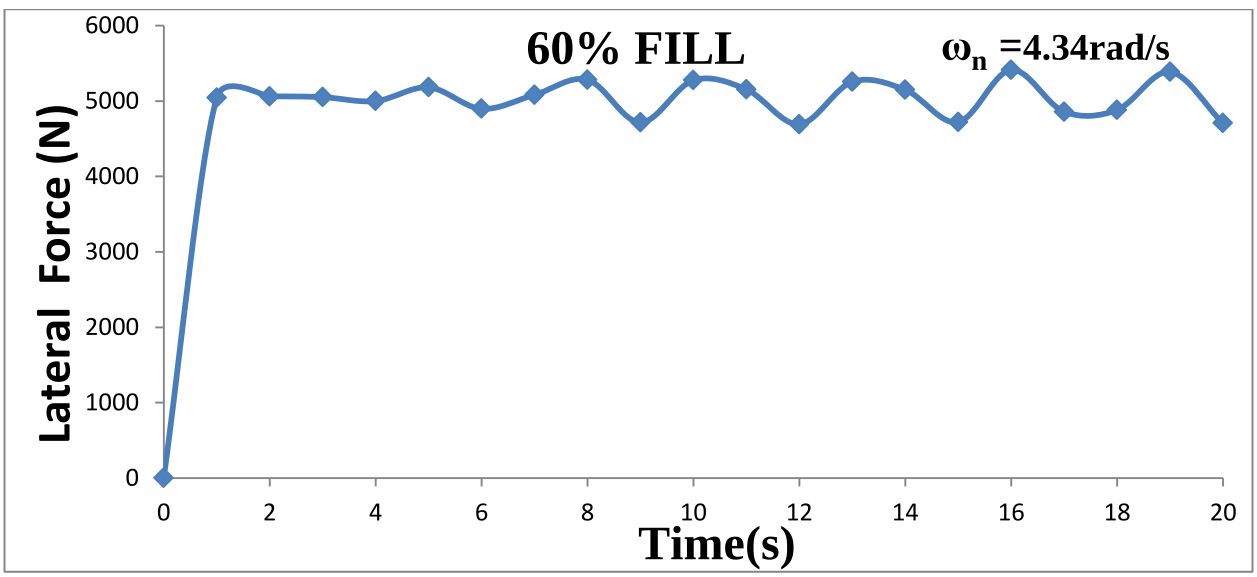


Fig 6.3: Lateral forces at 60% fill at Natural frequency (ω_n)

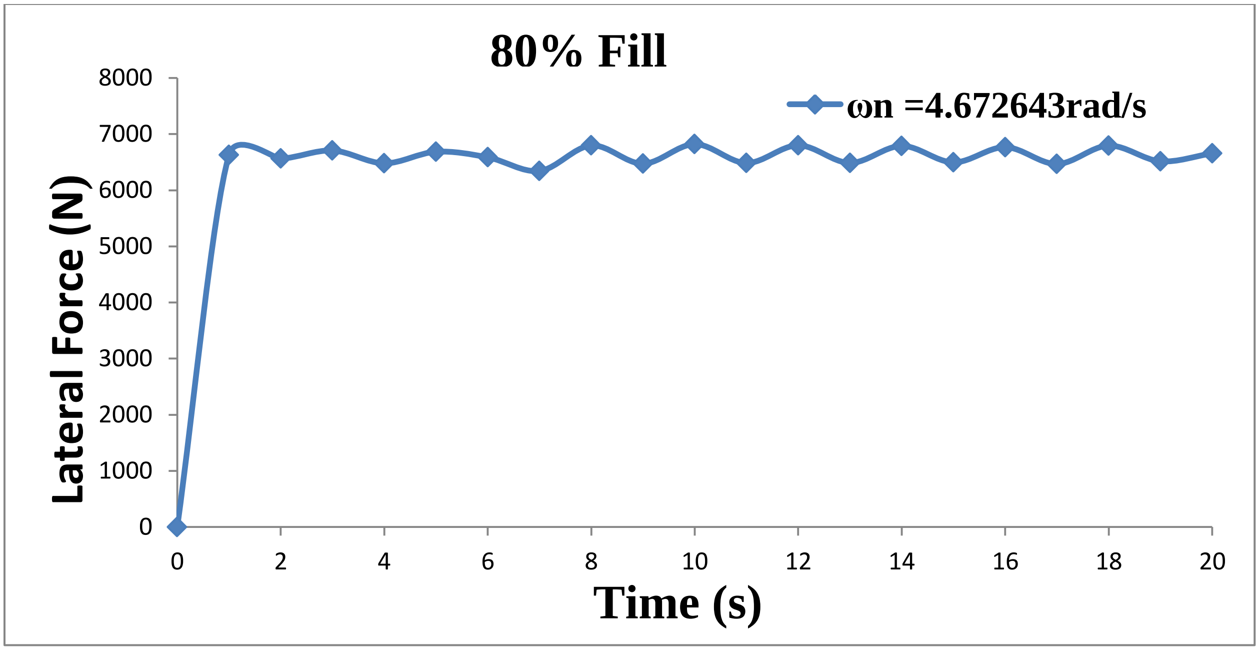


Fig 6.4: Lateral forces at 80% fill at Natural frequency (ω_n)

The above two Fig.6.3 and Fig.6.4 shows that variation in lateral forces is very low or it is insignificant in both cases fill level. It is because of the fact that tank is subjected to only longitudinal acceleration and this will not disturb lateral force amplification.

6.1.3 Fig 6.5 shows the comparison of longitudinal forces for 60% fill and 80% fill condition, when the tank is seismically excited by natural frequency with excitation amplitude of 0.015 m/s^2.

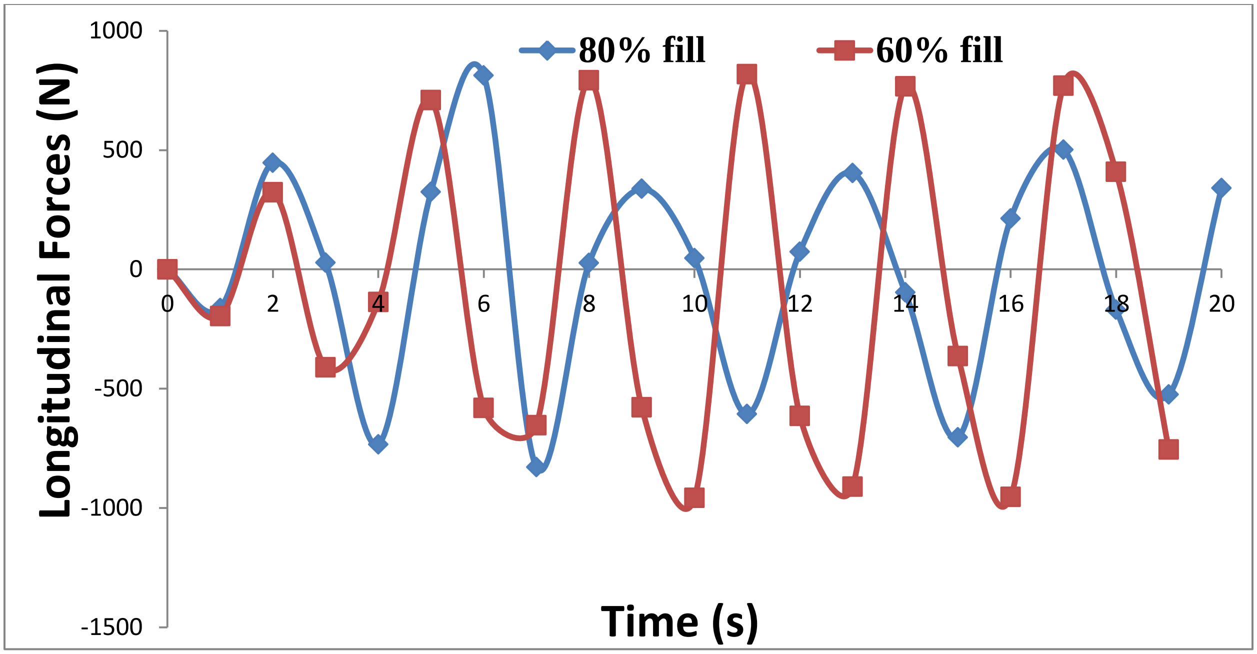


Fig 6.5: Longitudinal forces variation at 60% & 80% fill at Natural frequency (ω_n)

Fig 6.6 shows the comparison of lateral forces for 60% fill and 80% fill condition, when the tank is seismically excited by natural frequency with excitation amplitude of 0.015 m/s^2.

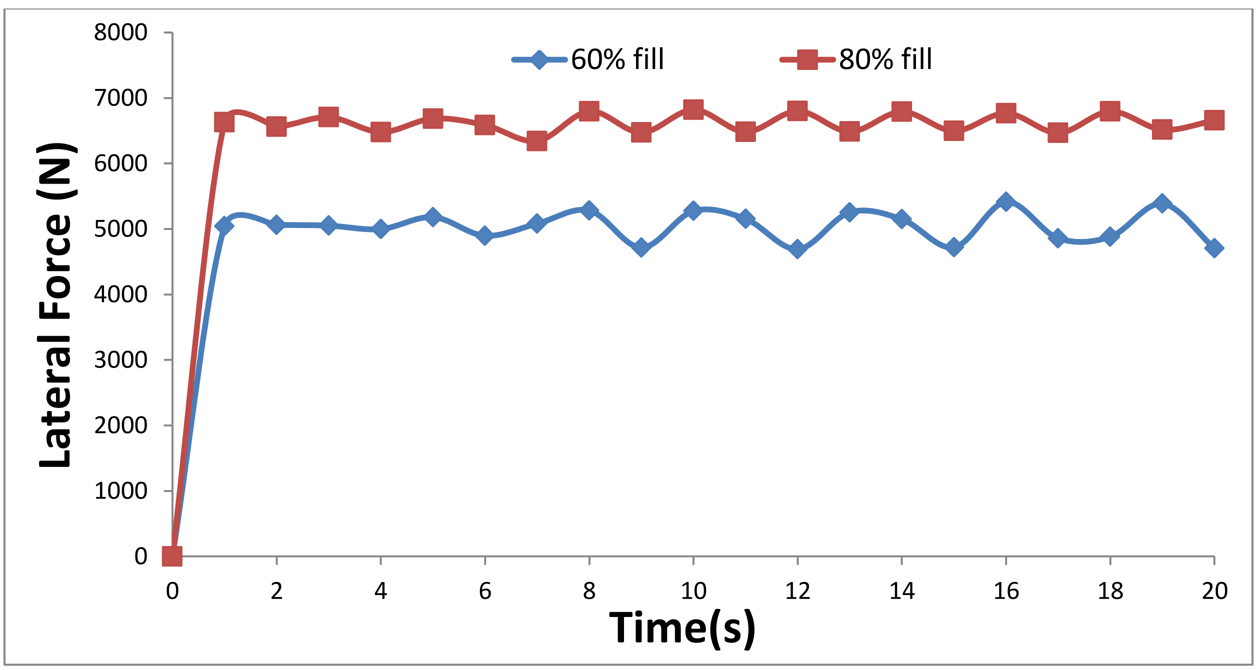


Fig 6.6: Lateral forces variation at 60% & 80% fill at Natural frequency (ω_n)

From above graphs it can be concluded that for longitudinal forces the maximum amplitude is higher at low fill level, because at higher fill level of fluid, slosh does not occur heavily, and for lateral forces the magnitude of force is higher in more fill level of tank (80%), as higher level create greater impact in roof of storage tank.

6.2 Case 2: When storage tank is subjected to Seismic Excitation of 0.93 times of Natural frequency ($0.93\omega_n$) without baffle.

6.2.1. Below fig 6.7 and fig 6.8 shows the graph for longitudinal forces variation vs. time at different fill level 60% and 80%, when the tank is subjected to Seismic Excitation of 0.93 times of Natural frequency ($0.93\omega_n$) without baffle with excitation amplitude of 0.015 m/s^2.

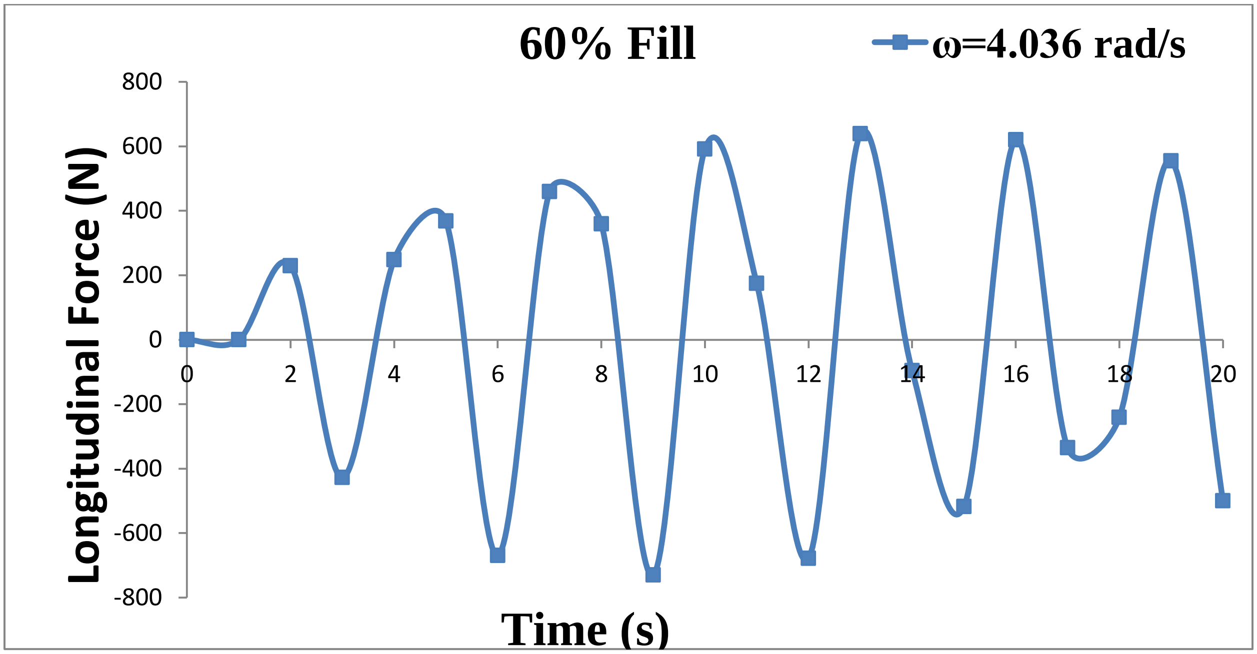


Fig 6.7: Longitudinal forces at 60% fill at 0.93 times of Natural frequency ($0.93\omega_n$)

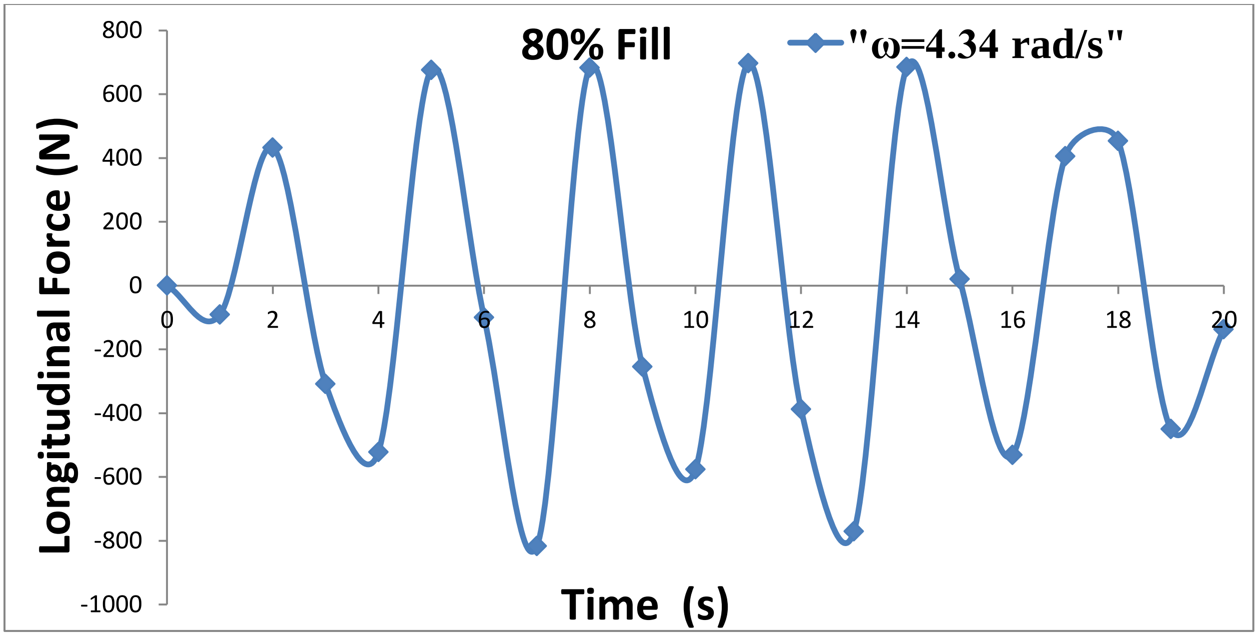


Fig 6.8: Longitudinal forces at 80% fill at 0.93 times of Natural frequency (0.93ω_n)

6.2.2. Below fig 6.9 and fig 6.10 shows the graph for lateral forces variation vs. time at different fill level 60% and 80%, when the tank is subjected to Seismic Excitation of 0.93 times of Natural frequency (0.93ω_n) without baffle with excitation amplitude of 0.015 m/s^2.

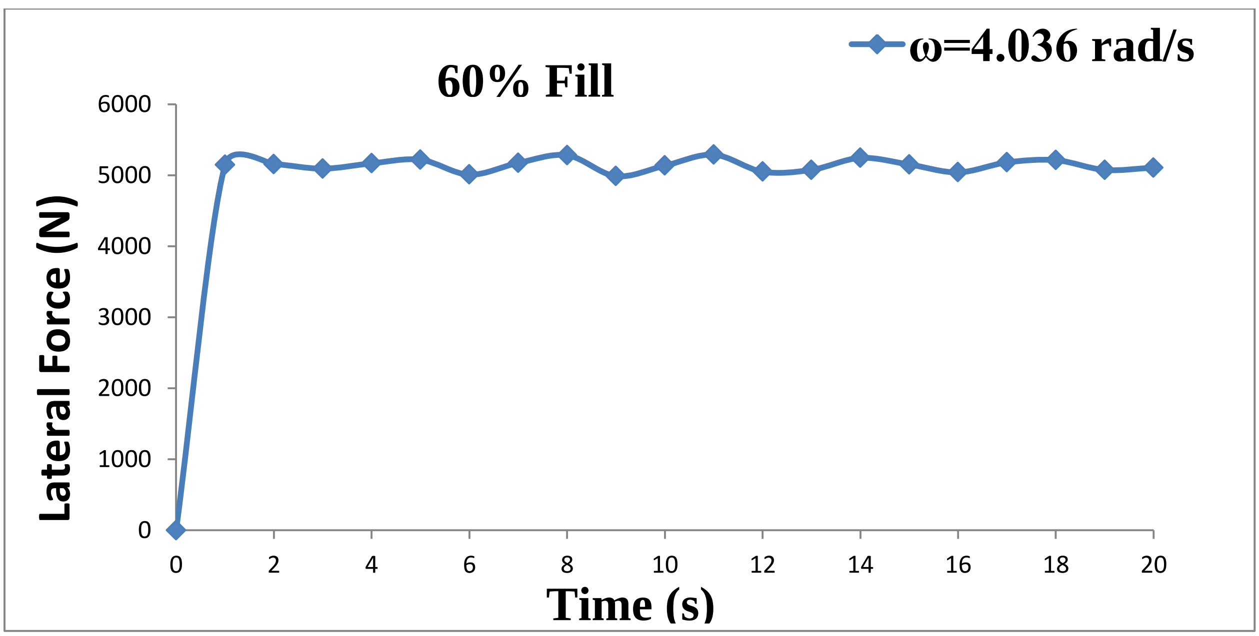


Fig 6.9: Lateral forces at 80% fill at 0.93 times of Natural frequency (0.93ω_n)

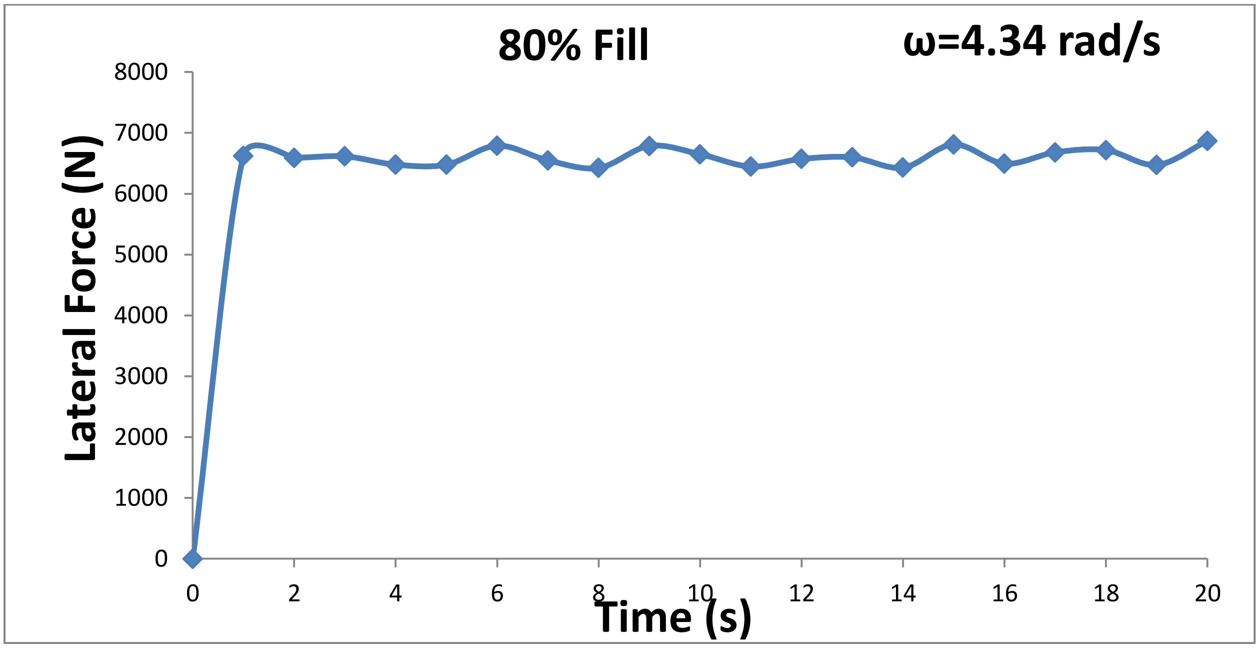


Fig 6.10: Lateral forces at 80% fill at 0.93 times of Natural frequency (0.93ω_n)

6.2.3 Fig 6.11 shows the comparison of longitudinal forces for 60% fill and 80% fill condition, when the tank is subjected to Seismic Excitation of 0.93 times of Natural frequency (0.93ω_n) without baffle with excitation amplitude of 0.015 m/s^2.

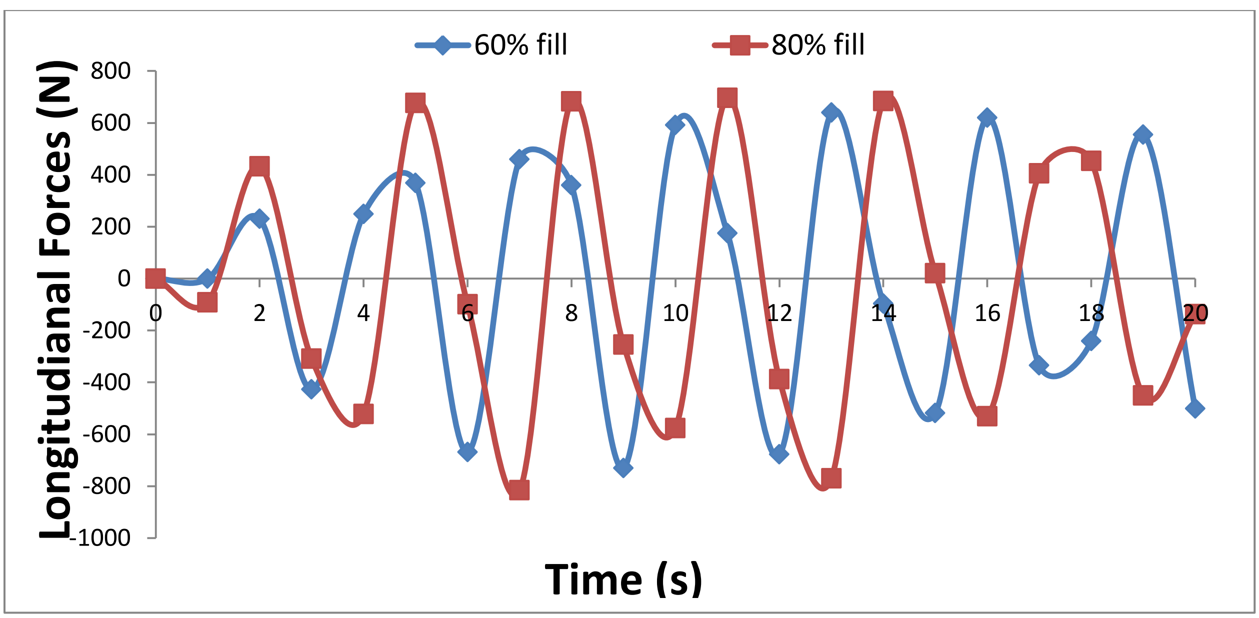


Fig 6.11: Longitudinal forces variation at 60% & 80% fill at 0.93 times of Natural frequency (0.93ω_n)

Fig 6.12 shows the comparison of lateral forces for 60% fill and 80% fill condition, when the tank is subjected to Seismic Excitation of 0.93 times of Natural frequency ($0.93\omega_n$) without baffle with excitation amplitude of 0.015 m/s^2

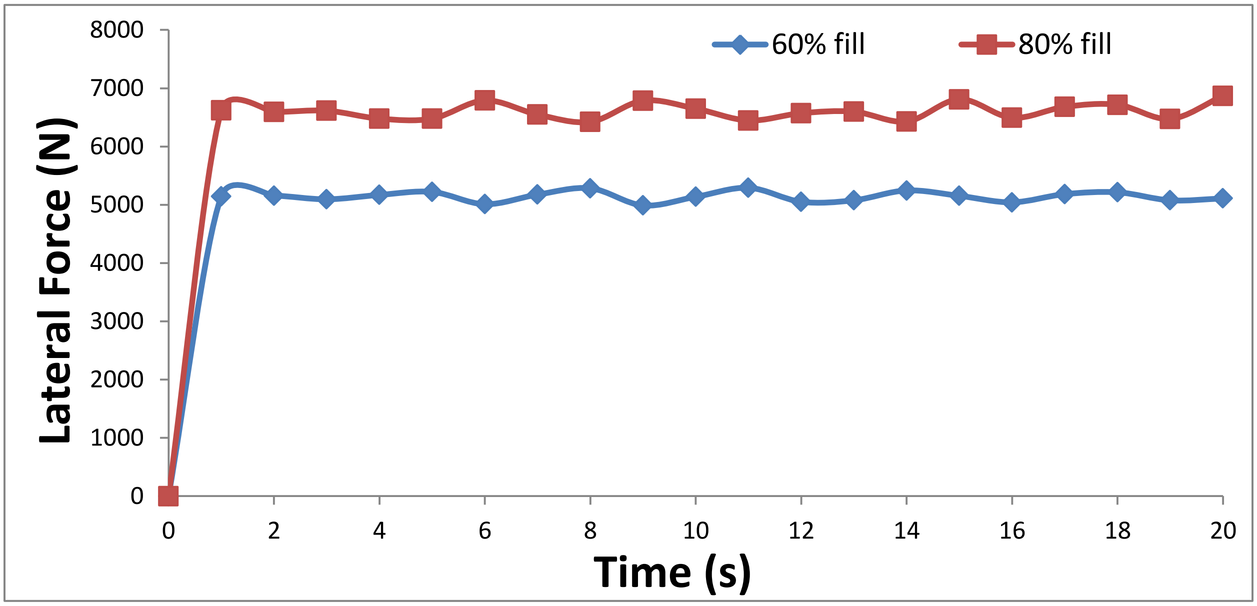


Fig 6.12: Lateral forces variation at 60% & 80% fill at 0.93 times of Natural frequency ($0.93\omega_n$)

From above graphs fig 6.11 & fig 6.12 it can be concluded that when the tank is excited by frequency less than natural frequency, for longitudinal forces the maximum amplitude is higher at low fill level, because at higher fill level of fluid, slosh does not occur heavily, and for lateral forces the magnitude of force is higher in more fill level of tank (80%), as higher level create greater impact in roof of storage tank.

6.2.4: Comparison of Longitudinal forces and Lateral forces at ω_n and $0.93\omega_n$ at different fill level

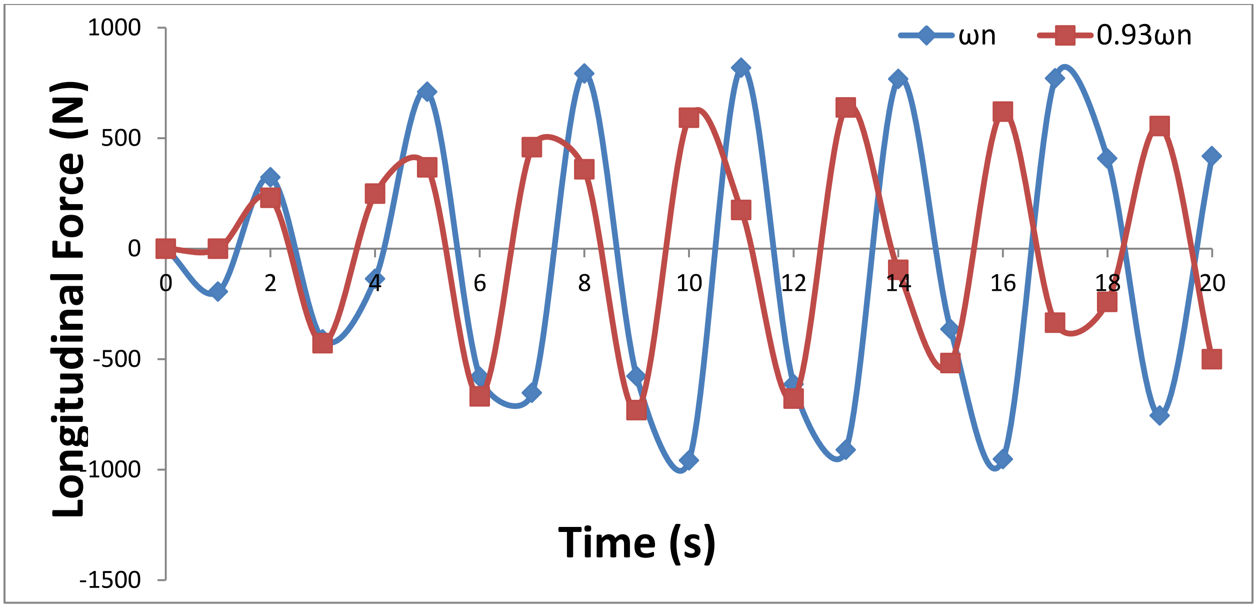


Fig 6.13: Longitudinal forces variation at ω_n and $0.93\omega_n$ at 60% fill level

From fig 6.13 and 6.14, it can be concluded that when the tank is seismically excited by higher frequency, tank wall suffers higher degree of longitudinal forces and the variation of amplitudes is much higher. For lateral forces magnitude of forces is nearly same but variation is greater in higher excitation.

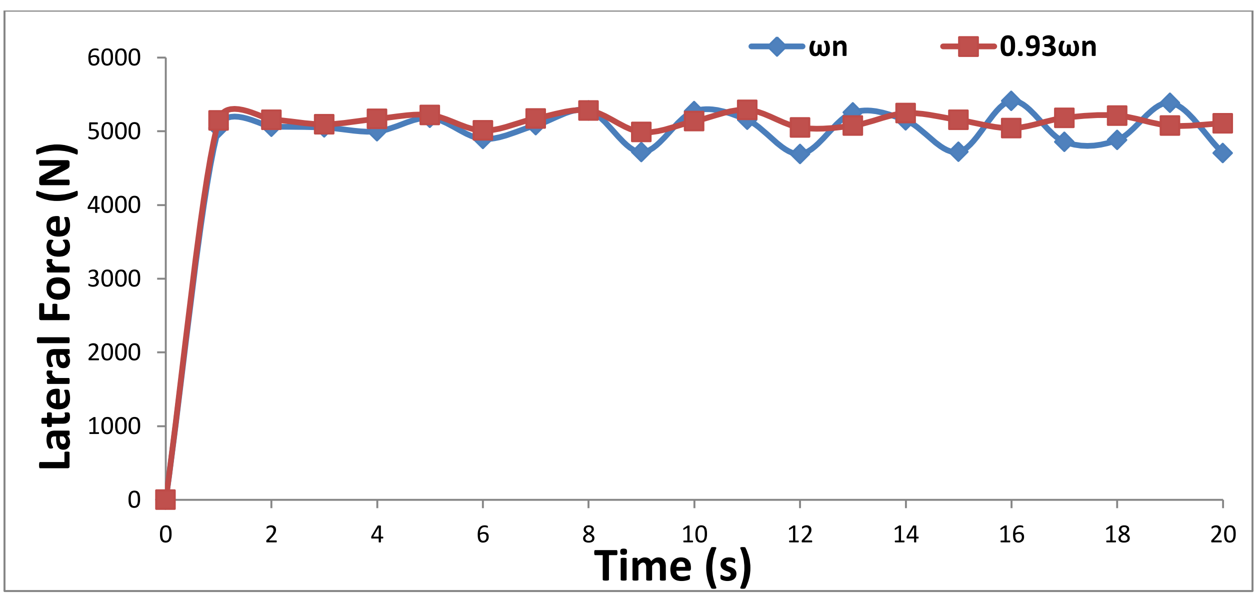


Fig 6.14: Lateral forces variation at ω_n and $0.93\omega_n$ at 60% fill level

6.3 Case 3: When storage tank is subjected to Seismic Excitation of Natural frequency (ω_n) with baffle height 0.3m.

6.3.1: Fig 6.15 & 6.16 shows the behavior of longitudinal forces at 60% and 80% fill when tank is equipped with baffle of height 0.3m and are excited by natural frequency (ω_n)

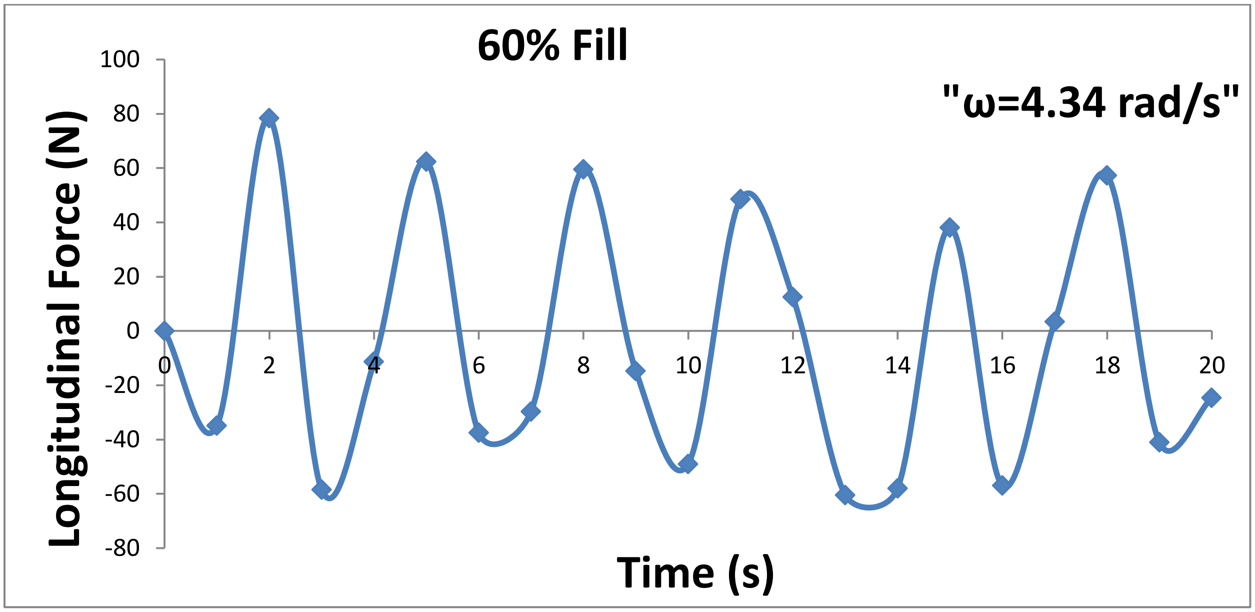


Fig 6.15: Longitudinal forces at 60% fill at Natural frequency

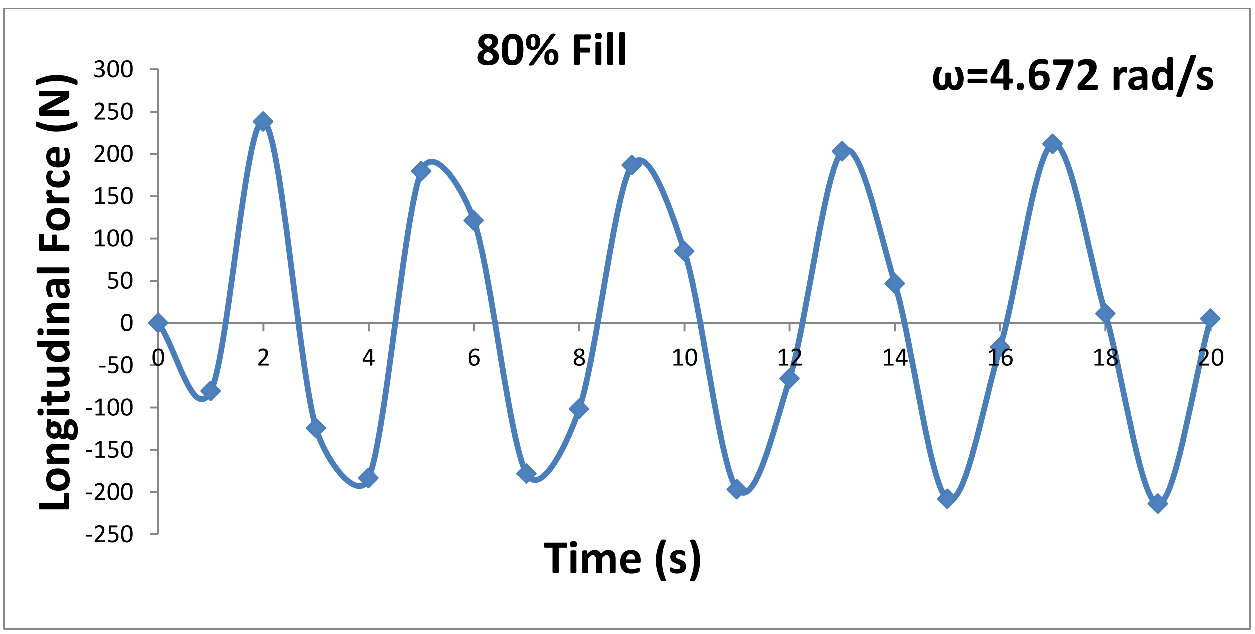


Fig 6.16: Longitudinal forces at 80% fill at Natural frequency

6.3.2: Fig 6.17 & 6.18 shows the behavior of lateral forces at 60% and 80% fill when tank is equipped with baffle of height 0.3m and are excited by natural frequency (ω_n).

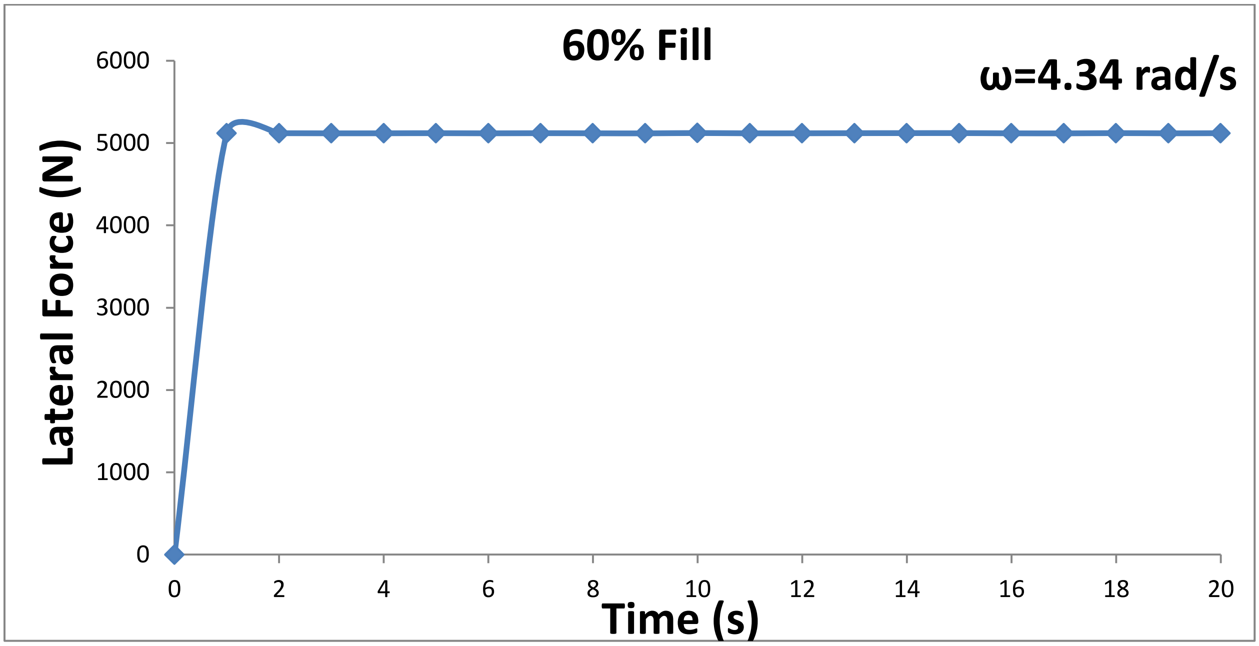


Fig 6.17: Lateral forces at 60% fill at Natural frequency

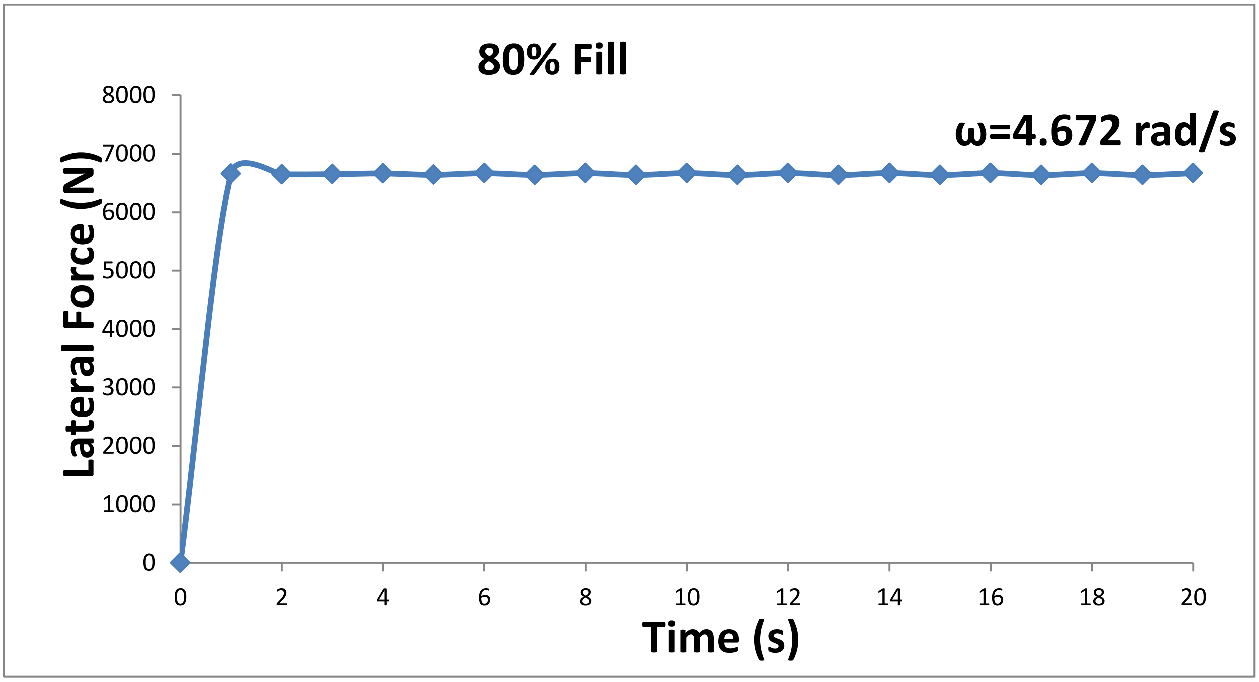


Fig 6.18: Lateral forces at 80% fill at Natural frequency

6.3.3 Fig 6.19 shows the comparison of longitudinal forces for 60% fill and 80% fill condition, when tank is equipped with baffle of height 0.3m and are excited by natural frequency (ω_n).

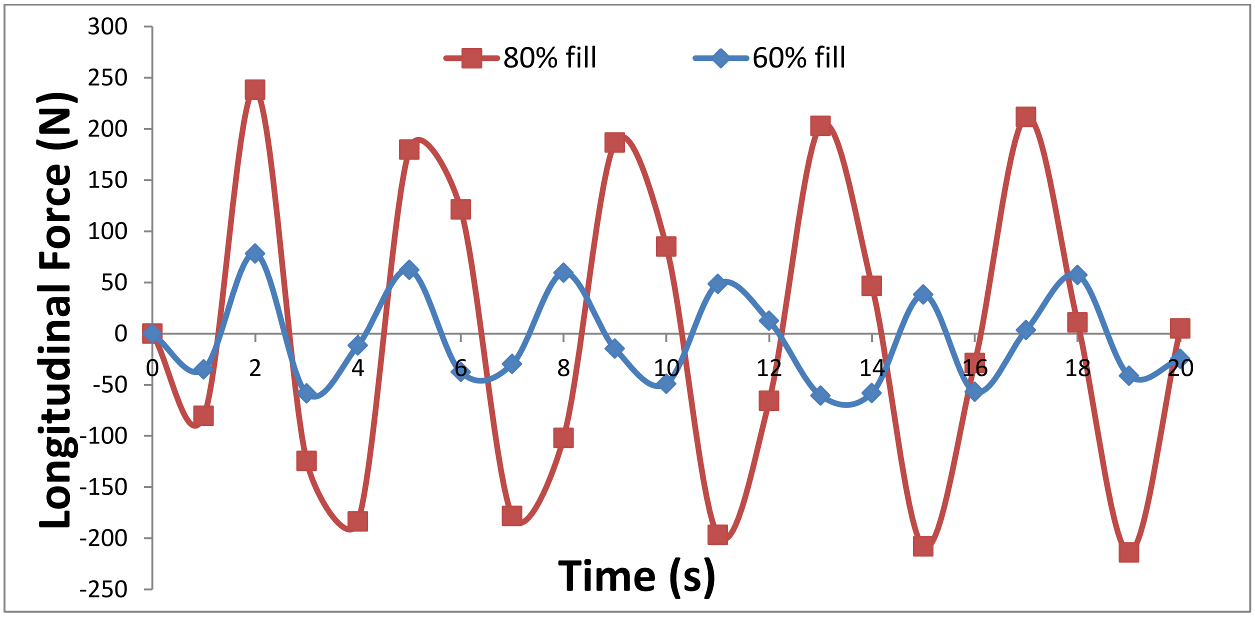


Fig 6.19: Longitudinal forces variation at 60% & 80% fill at Natural frequency with baffle

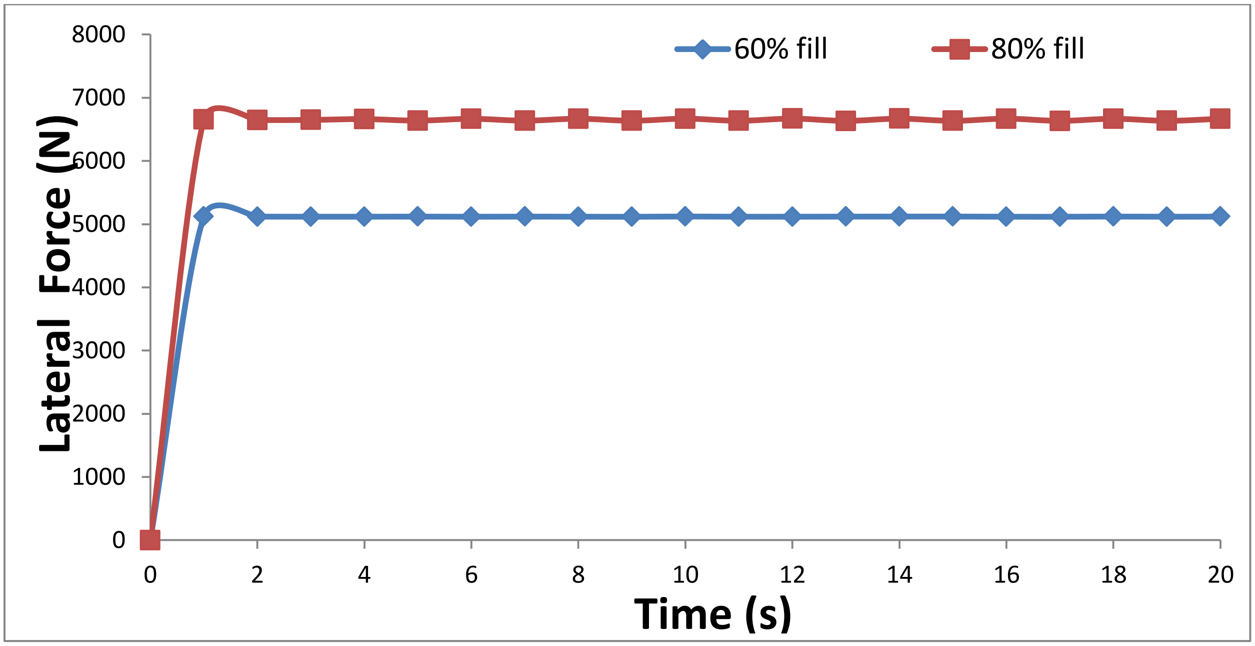


Fig 6.20: Lateral forces variation at 60% & 80% fill at Natural frequency with baffle

Above graphs fig 6.19 & fig 6.20 shows that, when the tank is equipped with baffle of height 0.3m, tank having fill level 60% observe less force in both cases of longitudinal as well as lateral than 80% fill because for 60% maximum part of slosh movement is affected by baffle as compared to later.

6.4 Case 4: When storage tank is subjected to Seismic Excitation of 0.93 times Natural frequency ($0.93\omega_n$) with baffle height 0.3m.

6.4.1 Fig 6.21 & 6.22 shows the behavior of longitudinal forces at 60% and 80% fill when tank is equipped with baffle of height 0.3m and are excited by 0.93 times Natural frequency ($0.93\omega_n$)

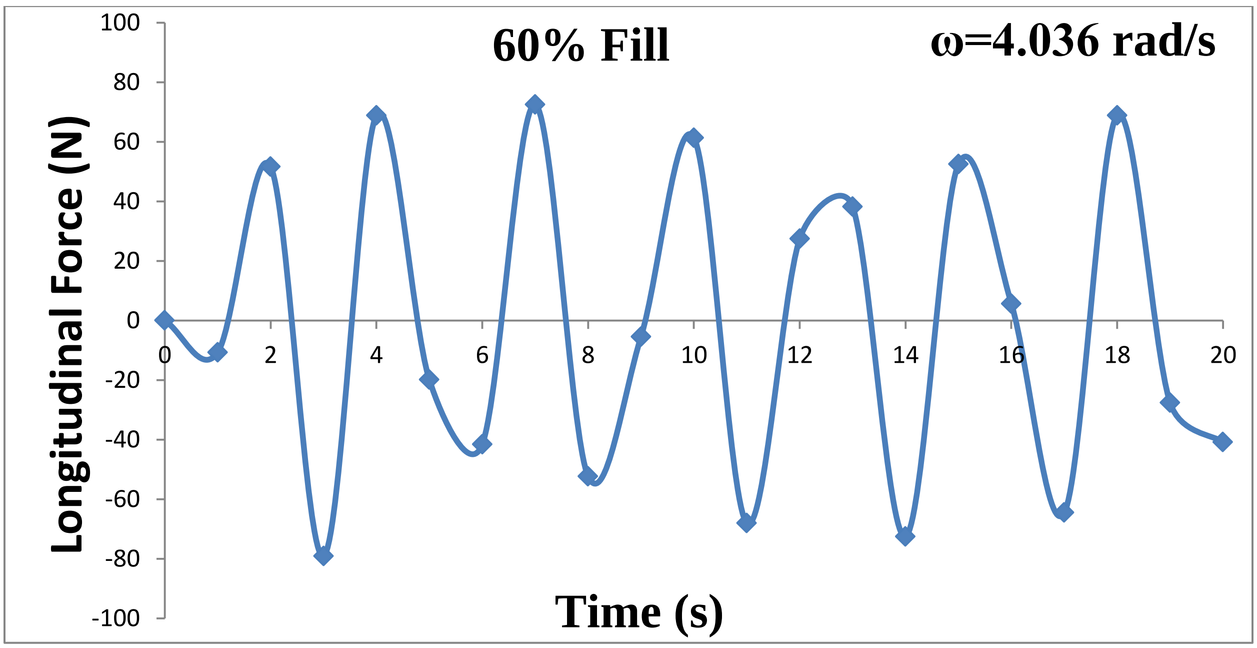


Fig 6.21: Longitudinal forces at 60% fill at ($0.93\omega_n$) with baffle

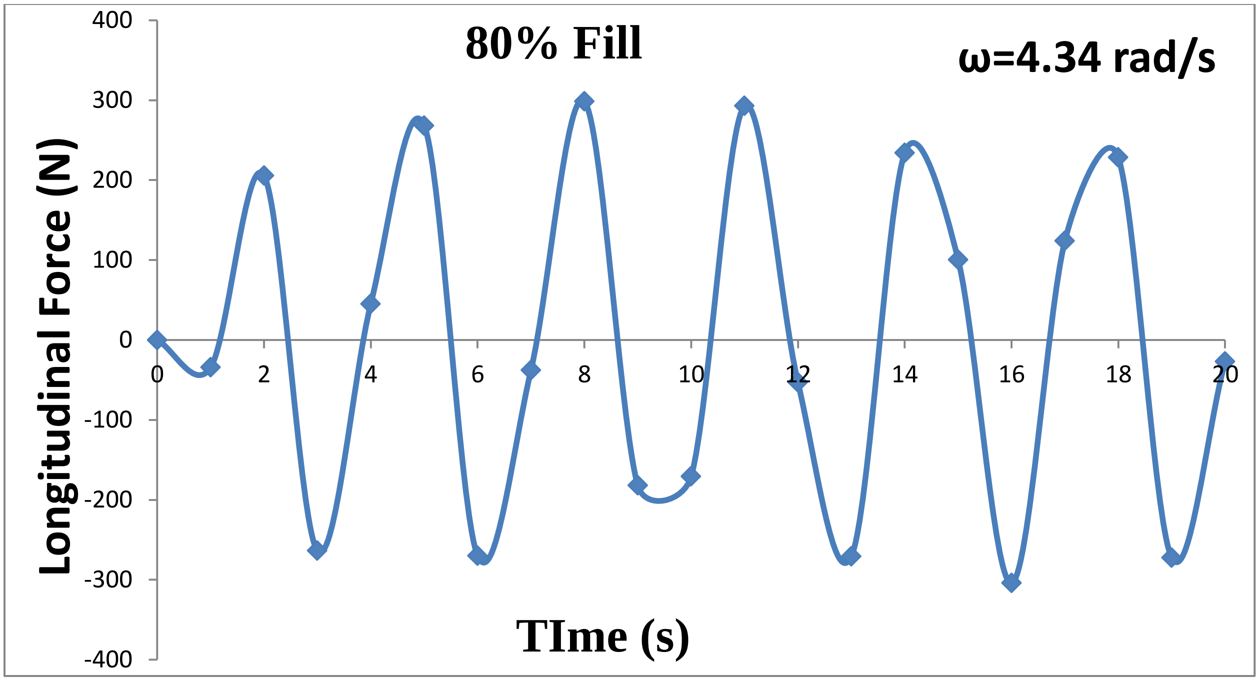


Fig 6.22: Longitudinal forces at 80% fill at ($0.93\omega_n$) with baffle

6.4.2 Fig 6.23 & 6.24 shows the behavior of lateral forces at 60% and 80% fill when tank is equipped with baffle of height 0.3m and are excited by 0.93 times Natural frequency ($0.93\omega_n$)

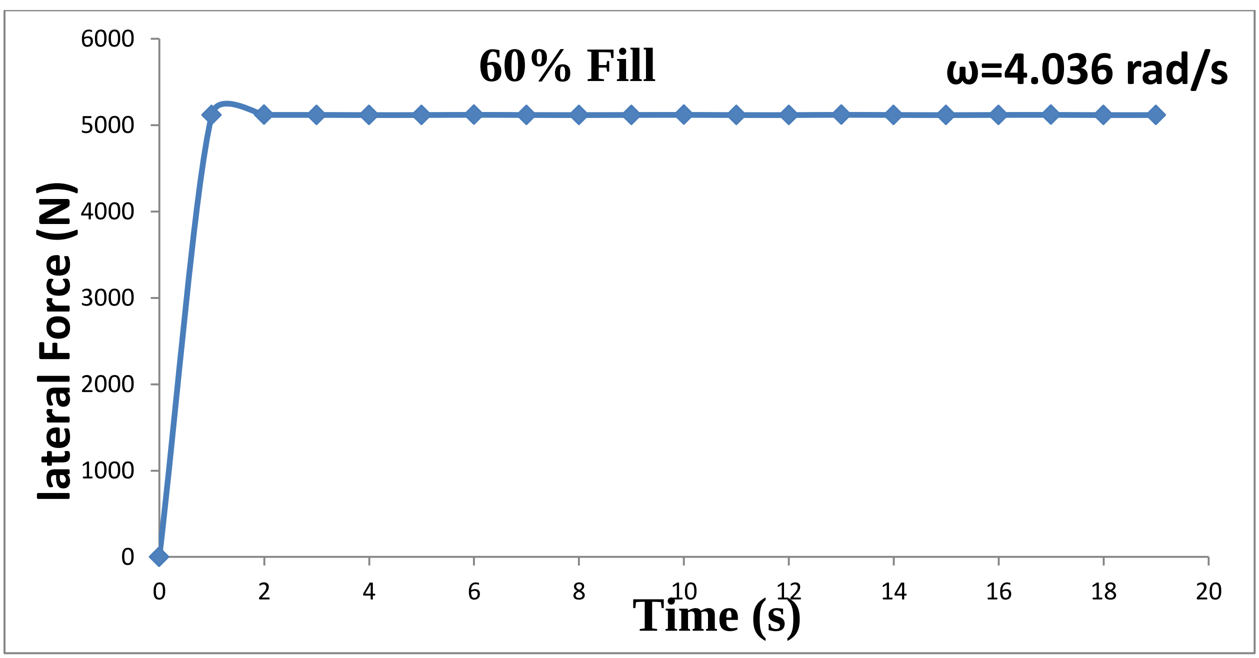


Fig 6.23: Lateral forces at 60% fill at ($0.93\omega_n$) with baffle

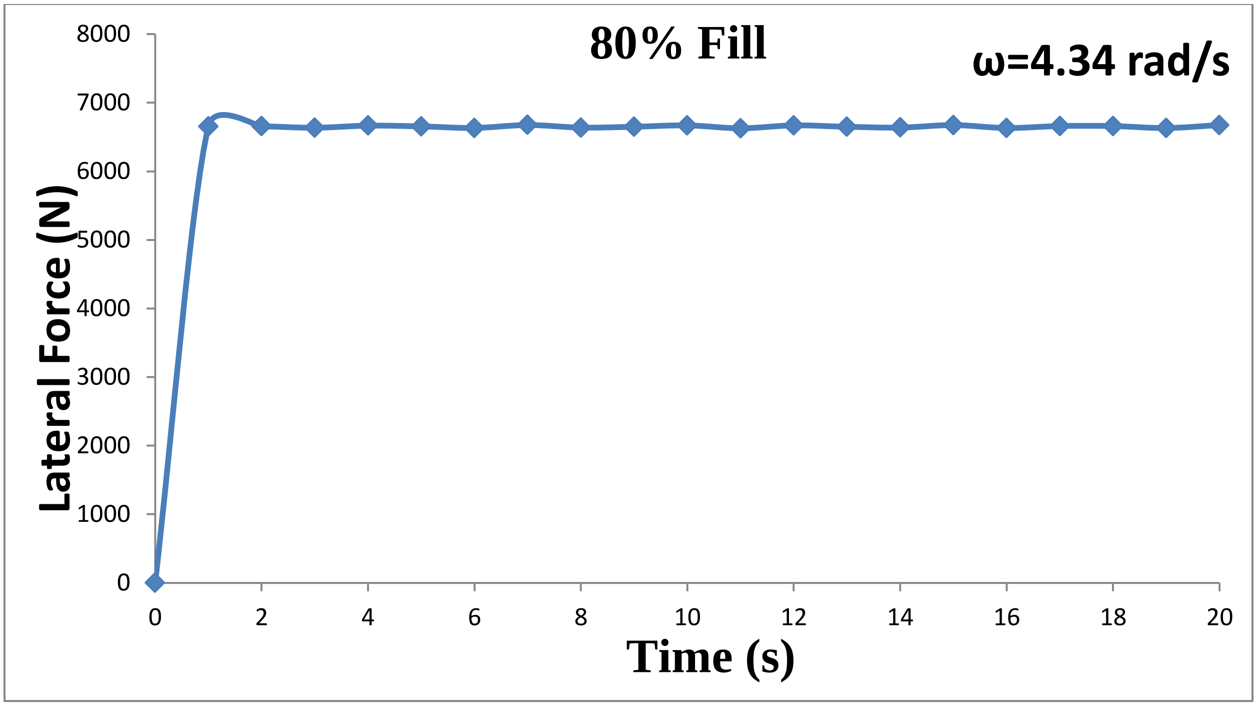


Fig 6.24: Lateral forces at 80% fill at ($0.93\omega_n$) with baffle

6.4.3 Fig 6.25 shows the comparison of longitudinal forces for 60% fill and 80% fill condition, when tank is equipped with baffle of height 0.3m and are excited by 0.93 times Natural frequency($0.93\omega_n$)

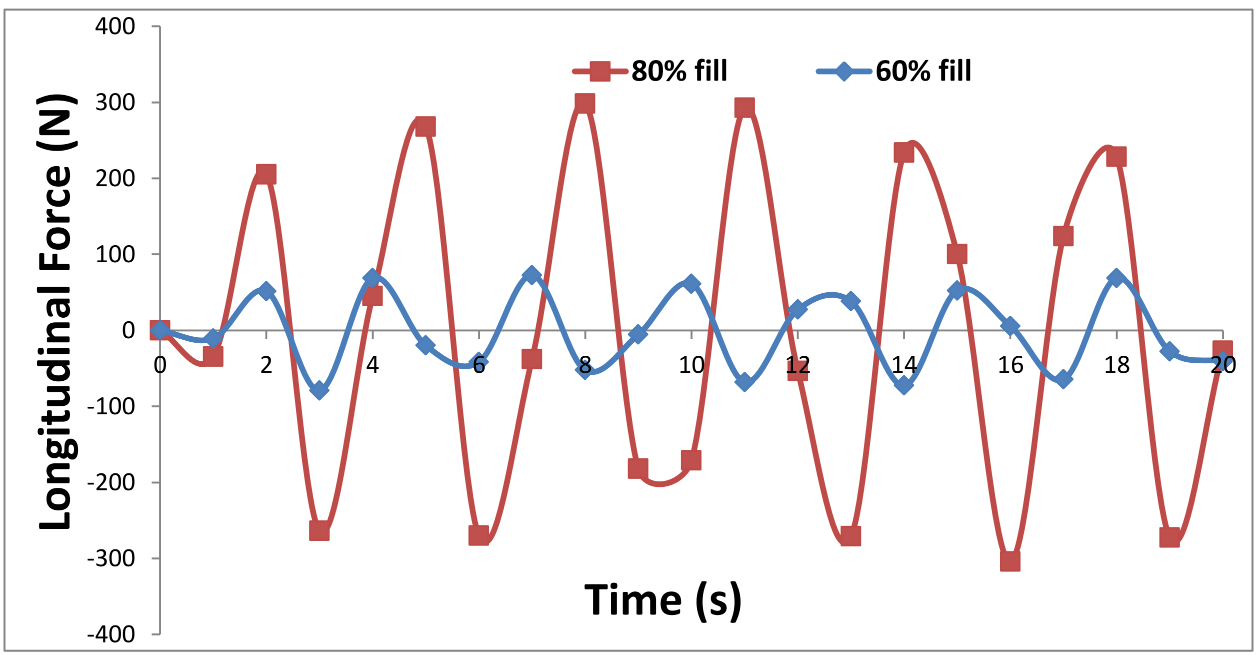


Fig 6.25: Longitudinal forces variation at 60% & 80% fill at $0.93\omega_n$ with baffle

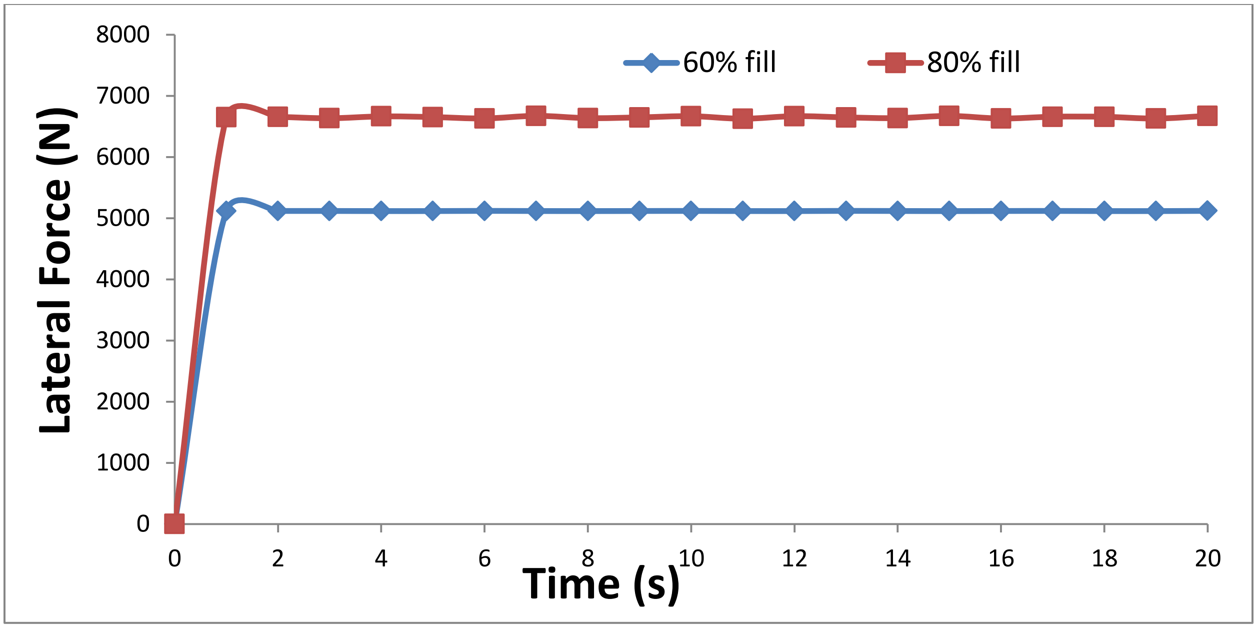


Fig 6.26: Lateral forces variation at 60% & 80% fill at 0.93ω_n with baffle

Above graphs fig 6.25 & fig 6.26 shows that, when the tank is equipped with baffle of height 0.3m and is excited by excitation frequency of lesser than 0.93ω_n, tank shows same behavior as that of $\omega_{n.}$ Tank having fill level 60% observe less force in both cases of longitudinal as well as lateral than 80% fill because for 60% maximum part of slosh movement is affected by baffle as compared to later.

6.5 Case 5: Comparison of Longitudinal and Lateral forces with and without baffles for 60% and 80% fill, when excited by 0.93 times of natural excitation frequency.

6.5.1 Fig 6.27 & 6.28 shows the behavior of longitudinal forces and lateral forces at 60% fill when tank is equipped with baffles of height 0.3m and 0.36m & without baffle, and are excited by 0.93 times of natural frequency (0.93ω_n)

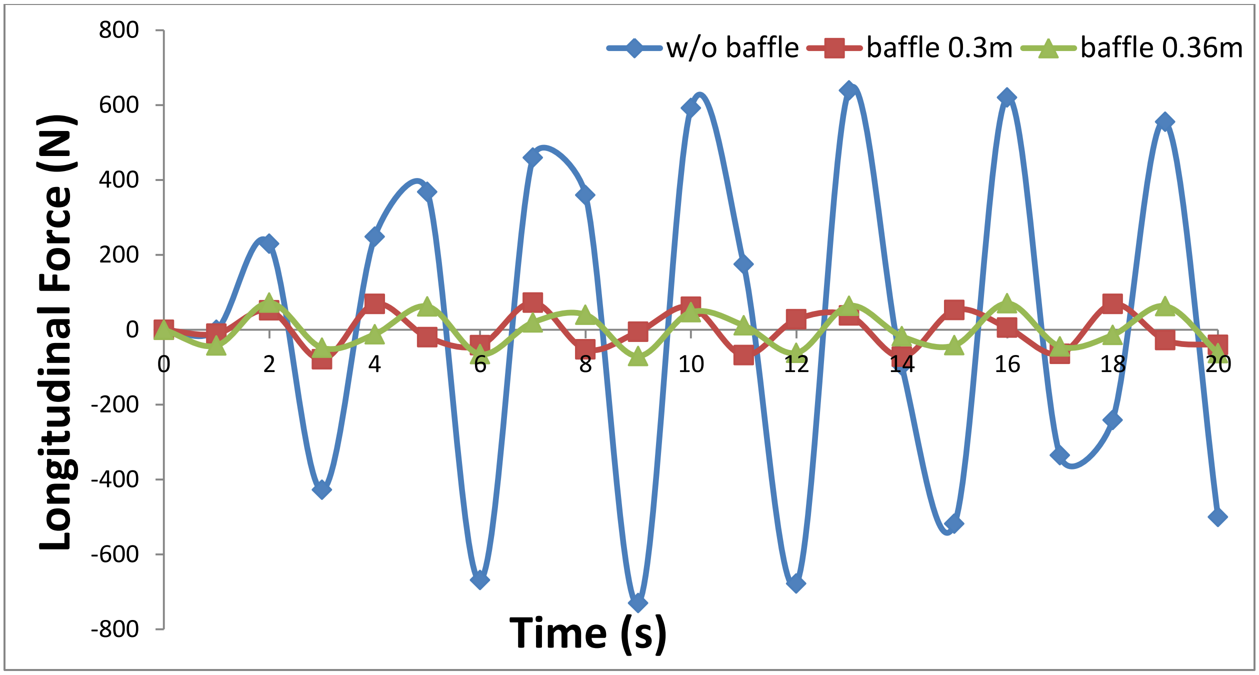


Fig 6.27: Comparison of Longitudinal forces variation for 60% fill at 0.93ω_n with baffle and without baffle

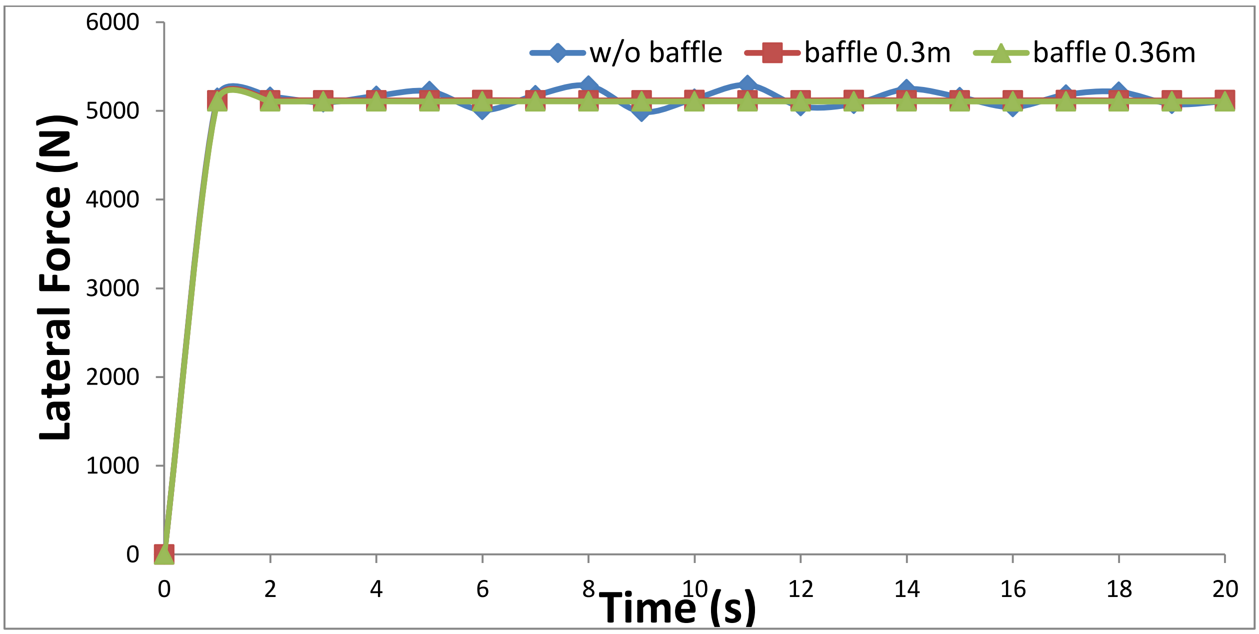


Fig 6.28: Comparison of Lateral forces variation for 60% fill at 0.93ω_n with baffle and without baffle

6.5.2 Fig 6.29 & 6.30 shows the behavior of longitudinal forces and lateral forces at 80% fill when tank is equipped with baffles of height 0.3m and 0.48m & without baffle, and are excited by 0.93 times of natural frequency (0.93ω_n)

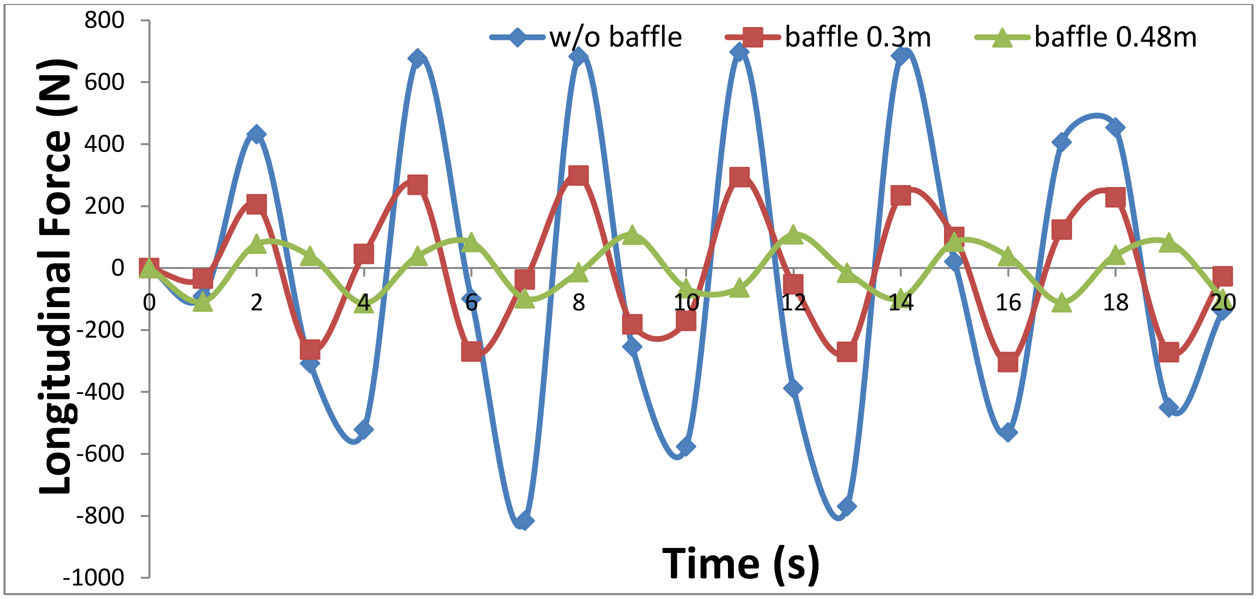


Fig 6.29: Comparison of Longitudinal forces variation for 80% fill at 0.93ω_n with baffle and without baffle

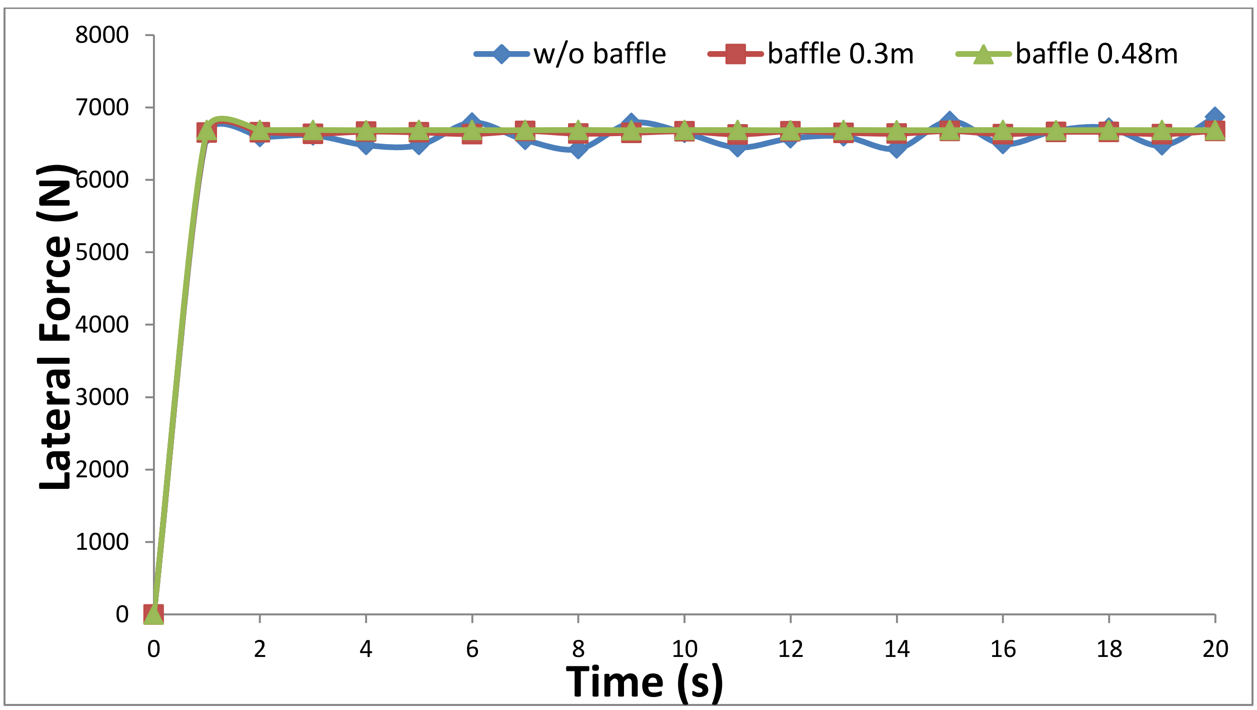


Fig 6.30: Comparison of Lateral forces variation for 80% fill at 0.93ω_n with baffle and without baffle

From above four graphs 6.27, 6.28, 6.29 & 6.30, it is clear that when tank is excited by 0.93ω_n, application of baffles can largely reduce the slosh impact on wall and provide sufficient damping. When the height of baffle is equal to fill level of tank, sloshing behavior is almost linear and does not create higher impact as compares to baffle with height 0.3m or without baffle.

In case of lateral forces, inclusion of baffle sufficiently reduces the roof impact due to slosh.

6.6 Case 6: Comparison of Longitudinal and Lateral forces with and without baffles for 60% and 80% fill, when excited excitation frequency of natural frequency ω_n.

6.6.1 Fig 6.31 & 6.32 shows the behavior of longitudinal forces and lateral forces at 60% fill when tank is equipped with baffles of height 0.3m and 0.36m & without baffle, and are excited by natural excitation frequency.

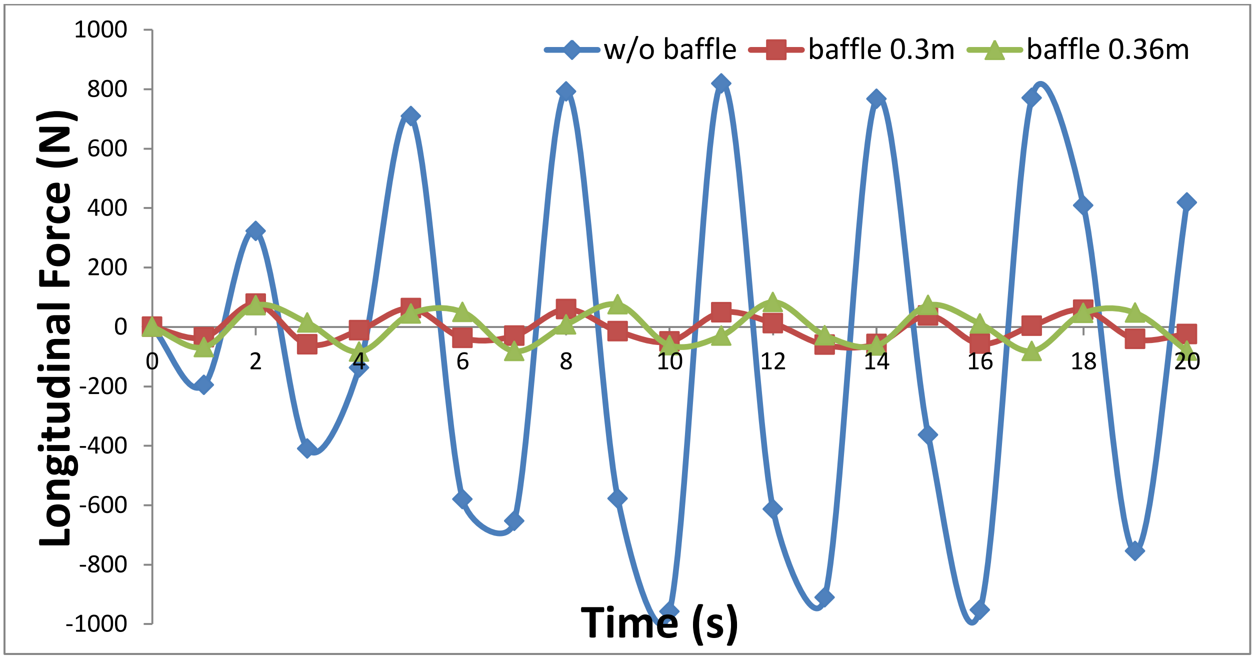


Fig 6.31: Comparison of Longitudinal forces variation for 60% fill at ω_n with baffle and without baffle

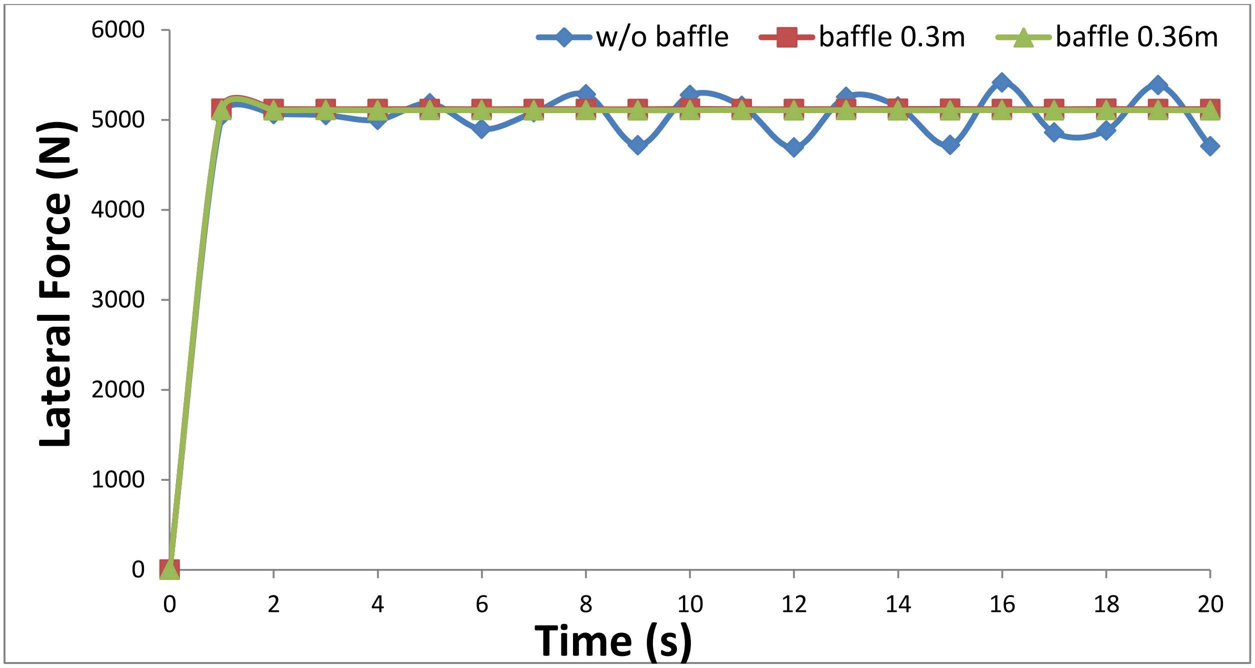


Fig 6.32: Comparison of Lateral forces variation for 60% fill at ω_n with baffle and without baffle

6.6.2 Fig 6.33 & 6.34 shows the behavior of longitudinal forces and lateral forces at 80% fill when tank is equipped with baffles of height 0.3m and 0.48m & without baffle, and are excited by natural excitation frequency ω_n.

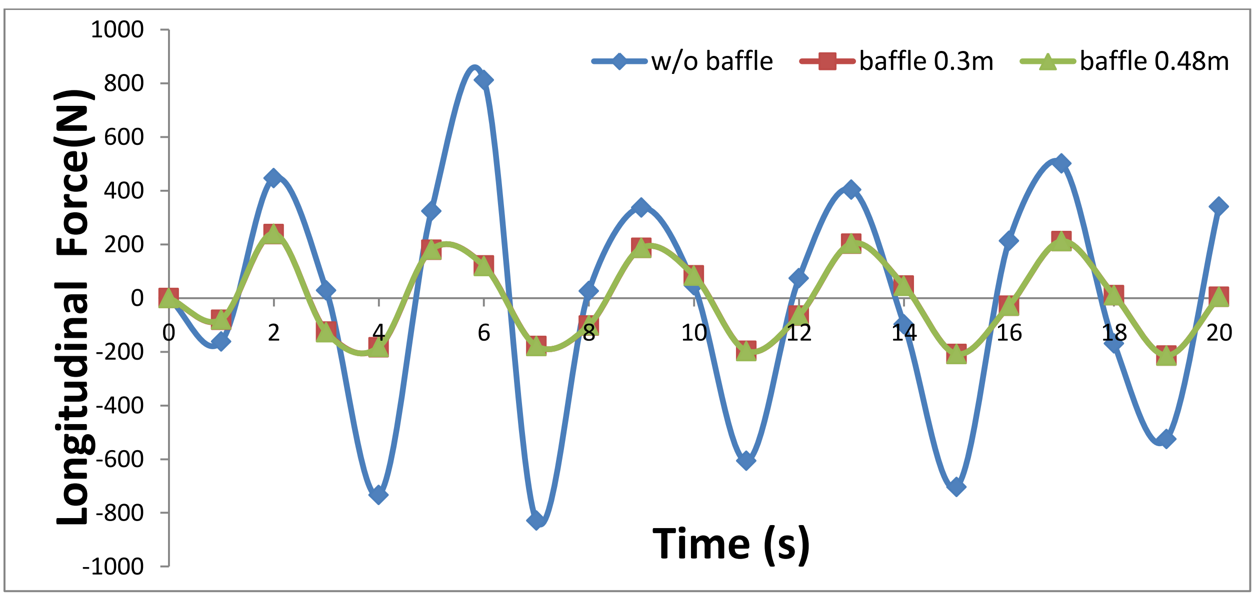


Fig 6.33: Comparison of Longitudinal forces variation for 80% fill at ω_n with baffle and without baffle

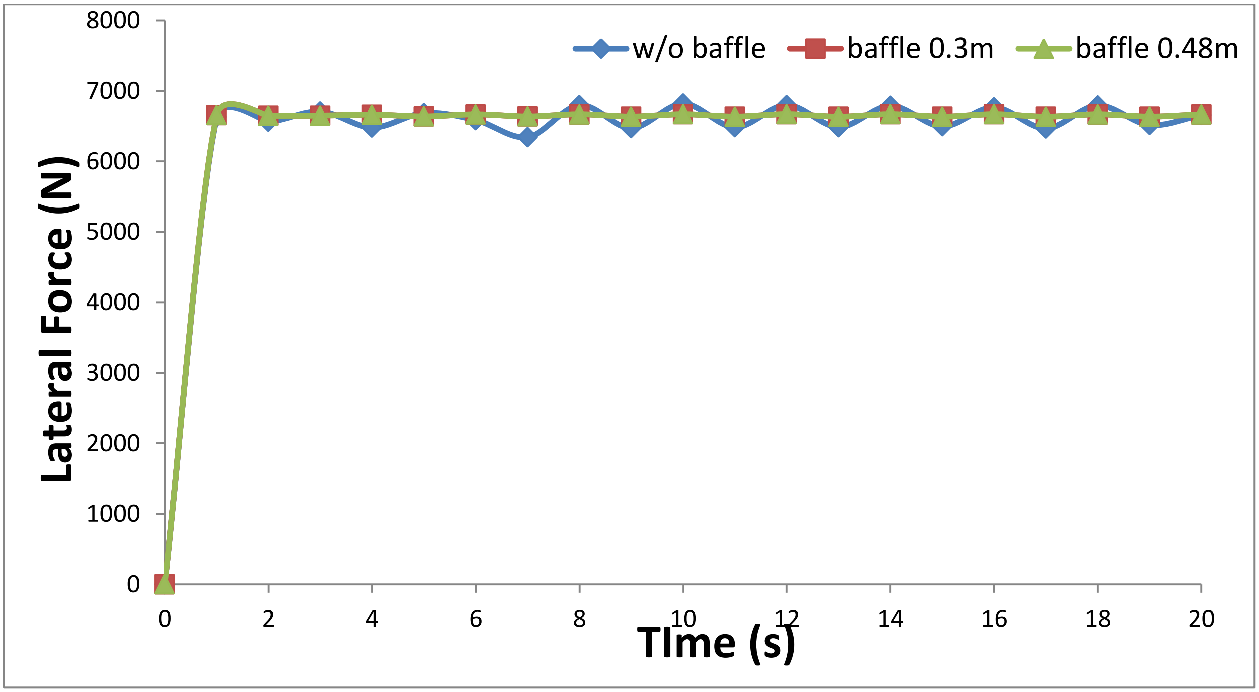


Fig 6.34: Comparison of Lateral forces variation for 80% fill at ω_n with baffle and without baffle

From above four graphs 6.31, 6.32, 6.33 & 6.34, it is clear that when tank is excited by ω_n, the forces amplification is higher and application of baffles can largely reduce the slosh impact on wall and provide sufficient damping. When the height of baffle is equal to fill level of tank, sloshing behavior is almost linear and does not create higher impact as compared to baffle with height 0.3m or without baffle.

In case of lateral forces, inclusion of baffle sufficiently reduces the roof impact due to slosh.

Chapter 7

Conclusion and Future Work

Liquid sloshing in 3-D water storage tank with and without baffles is investigated. It is evident from the CFD transient simulations of liquid interface carried out at various time steps for both configurations (with and without baffle) of tank that impact of sloshing reduces significantly by the use of baffles.

From the above analysis, it can be seen that sloshing loads will be higher if the tank is excited by natural frequency near resonant condition, liquid sloshing will become violent, show overturning, and create severe impact on the top wall of the tank. To reduce the impact of sloshing forces in tank wall, baffles are provided inside the tank, which can work as a damper and sufficiently reduce the amount of slosh waves. It can be predicted that the larger the fill level of tank, greater the complexity of liquid sloshing.

For the future research, different other configurations of baffles can be analyzed to optimize the design of the tank to further reduce the sloshing phenomenon. The dimensions of the baffles can also be optimized for further reduction in the sloshing. Sloshing under more seismic excitation amplitude can also be investigated. The transient as well steady-state moments caused by fluid slosh under simultaneously applied horizontal and vertical excitation can also be evaluated.

The investigation can also be preceded for nuclear storage tanks during earthquake.

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